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grade 13 pssc physics macrocosms & microcosms

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January–May Series

Macrocosms and Microcosms

A SERIES OF PROGRAMS BASED ON
THE GRADE 13 PHYSICS COURSE

Ontario Educational Television
Ontario Department of Education

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Macrocosms and Microcosms

GENERAL INTRODUCTION

This booklet contains teacher's guide information for the last sixteen programs in this series; these will be shown from January to May. This constitutes the second half of the guide book which was sent out in September.

Program 10
Free Fall and Projectile Motion

This program follows naturally from the previous one, in that it provides further experimental evidence for the laws discovered there. It relates directly to sections 20-1, 2, 3, 4 of the PSSC text (2nd ed.) and reference should also be made to sections 6-5, 7-2, and 7-3. The complete PSCC film *Free Fall and Projectile Motion* with Prof. Nathaniel H. Frank of the Massachusetts Institute of Technology is shown.

MAJOR POINTS OF THE PROGRAM

1. If the behaviour of freely falling bodies under the force of gravity is to be studied, then the effect of the air must be eliminated. The presence of the air can cause a variety of effects. For objects which are relatively dense, the air resistance can be neglected compared to the weight.
2. Under the force of gravity alone, all objects at the same place fall with the same accelerated motion.
3. A direct consequence of the above result is that inertial mass is proportional to gravitational mass. The reasoning used in the film is summarized below:
From Newton's Law $F = m_i a$
but F is the pull of gravity or the weight of the object, and we know that $F = m_g g$, where g is the gravitational field strength or force per unit mass.

Therefore $m_i a = m_g g$

But we know that g is the same for all bodies at the same place, and we also found experimentally that a is the same for all bodies at the same place, therefore $m_i \propto m_g$.

Since the same unit has been chosen for both, namely the Standard Kilogram, we say that $m_i = m_g$ and this is the reason that we use the word 'mass' for both these quantities.
4. The question is then asked, "Does the downward gravitational pull of the earth cause the same downward acceleration for curved motion as it does for a body falling freely from rest?". It is emphasized that such a question can only be answered experimentally. The experiment is performed in two different ways. The analysis of the motion of two balls from a 'projectile apparatus' by slow motion photography in both the vertical and horizontal directions is very striking. The vector nature of Newton's Law is indicated from the results of the experiment.
5. Another fact which is indicated from the results of the experiment is that inertial mass is a scalar quantity.
6. A third idea which develops from the experiment is the independence of perpendicular components of a motion. The usefulness of the independence of horizontal and vertical motions is shown by solving what at first appears to be a very complicated problem, viz.: Where do you aim to shoot a monkey in a tree, who drops from the tree the moment the bullet leaves the muzzle, when you do not know the speed of the bullet, the distance to the monkey or the angle of elevation of the monkey? The solution is developed in theory and then demonstrated experimentally.
7. In summarizing the points of the lesson, Prof. Frank mentions the fact that we also find the acceleration due to gravity to be *constant* over the distances we use to measure it. His way of looking at this is rather unique in that he says it is relatively unimportant because all it tells us is how small we are compared to the size of the earth.

POINTS FOR FURTHER DISCUSSION AND AMPLIFICATION

1. The distinction between gravitational and inertial mass hinges on the fact that physical quantities are defined by the way they are measured. Since gravitational mass and inertial mass are measured in two entirely different and unrelated ways, they are treated as two different properties of matter. The fact that they are proportional is derived only from experiments. Their numerical equivalence derives only from the choice of a common unit.
2. The gravitational field intensity (g) of the earth is defined as force per unit *gravitational* mass. Therefore g becomes numerically equal to the acceleration due to gravity (a) only after the numerical equivalence of m_i and m_g has been established.

Program 11
Frames of Reference

INTRODUCTION

In the realm of kinematics we may use any frame of reference we wish to describe the motion of an object. It is usual to select the frame of reference which gives the simplest description of motion. This program, however, will indicate that this cannot be done when attempting a dynamical description of motion. Our laws of motion do not apply in all frames of reference.

As the whole PSSC film is shown in this program, little time is left for any other comments. Students, however, should be encouraged to make notes during the broadcast and bring them to class for discussion. On the other hand, the students might be given a list of the major points of the program in advance of the broadcast. They could then look for them during the viewing of the telecast.

MAJOR POINTS OF INTEREST

The following is a list of demonstrations and important ideas represented in the program:

1. All motion is relative. When an object is moving, it is usually thought of as moving relative to something else which is 'fixed'. Since motion is a vector quantity, it must be described relative to a 'frame of reference' which consists of a co-ordinate system having x, y, and z axes. Furthermore, the frame of reference is attached to the so-called 'fixed' object. For example, in most of our normal experiences of motion we use a frame of reference attached to the earth.
2. A steel ball is dropped from an electromagnet which is at rest, relative to a frame of reference attached to the earth. The experiment is repeated in a frame of reference moving at a constant velocity to the earth. It is viewed from an earth frame of reference and from a frame of reference attached to a moving cart. The motion of the ball appeared identical (a) when the cart was standing still and (b) when the cart was moving at constant velocity *and* the ball was viewed *in the frame of reference of the moving cart.*

   Conclusion: All frames of reference moving at constant velocity with respect to one another are equivalent.
3. From a kinematics viewpoint one tends to put oneself in the simplest frame of reference and one does not *always* view everything from the earth's frame of reference. This point is made by observing the motion of a spot near the circumference of a rolling wheel.
4. The relationship $\vec{u} + \vec{v}$ for comparing velocities in one frame of reference with those in another frame of reference is demonstrated. This formula for relative velocity does not apply at speeds approaching the speed of light.
5. The motion of the falling ball is observed in an accelerated frame of reference. The distinction between inertial and non-inertial frames of reference is outlined in the program. An inertial frame of reference is one in which Galileo's Law of Inertia is supported.
6. An accelerated frame of reference is a non-inertial frame of reference because in it, an object appears to be accelerated with *no* unbalanced force! In order to be able to use the Law of Inertia relative to a non-inertial frame of reference, the idea of fictitious forces is introduced. For example, instead of thinking of the frame of reference as being accelerated, it is treated as if it were fixed, and it is imagined that there is a force acting on the object to cause the observed acceleration relative to the frame of reference. The direction of this fictitious force is always opposite to the direction in which the frame of reference is actually being accelerated.
7. A rotating frame of reference is also an accelerated frame of reference and therefore, a non-inertial frame of reference. The fictitious force which is introduced in the rotating frame of reference to make the law of inertia remain true is called the centrifugal force. When a rotating object is viewed in an inertial frame of reference, there is *only* the centripetal force; the centrifugal does not exist.
8. Because the earth is rotating on its axis, it must be a non-inertial frame of reference. In the earth frame of reference, the fictitious centrifugal force is only 3/100 of a newton – even at the equator. As this is so small, it is usually ignored and the earth is treated as an inertial frame of reference.
9. The Foucault pendulum is explained as the means by which it is established that the earth is rotating about its north-south axis.

FURTHER DISCUSSION AND EXAMPLES

1. It should be indicated that where the words "watch for involute now" are superimposed on the screen during the broadcast, this is not the only place where an involute may be observed. This point of indication, however, is where an involute may be seen most clearly without any distraction.

2. An involute is the path as seen in a rotating frame reference of an object moving at constant speed in a straight line in an inertial frame of reference. It is best understood by drawing it as follows:

X Y is the path of an object A, moving at constant speed in a straight line. The observer B is rotating about O at constant angular velocity. The positions of each in an inertial frame of reference are represented by numbers 1 to 16 as shown in Figure 1.

In order to see what the path A looks like from B's point of view, position vectors must be drawn from B to A at successive equal time intervals and all be brought to a common point of origin. It must be remembered that the observer B is *not* aware of the fact that he is rotating. B believes that he is in a 'fixed' world and that only A is moving relative to him. The solution is indicated as follows in Figure 2 and Figure 3:

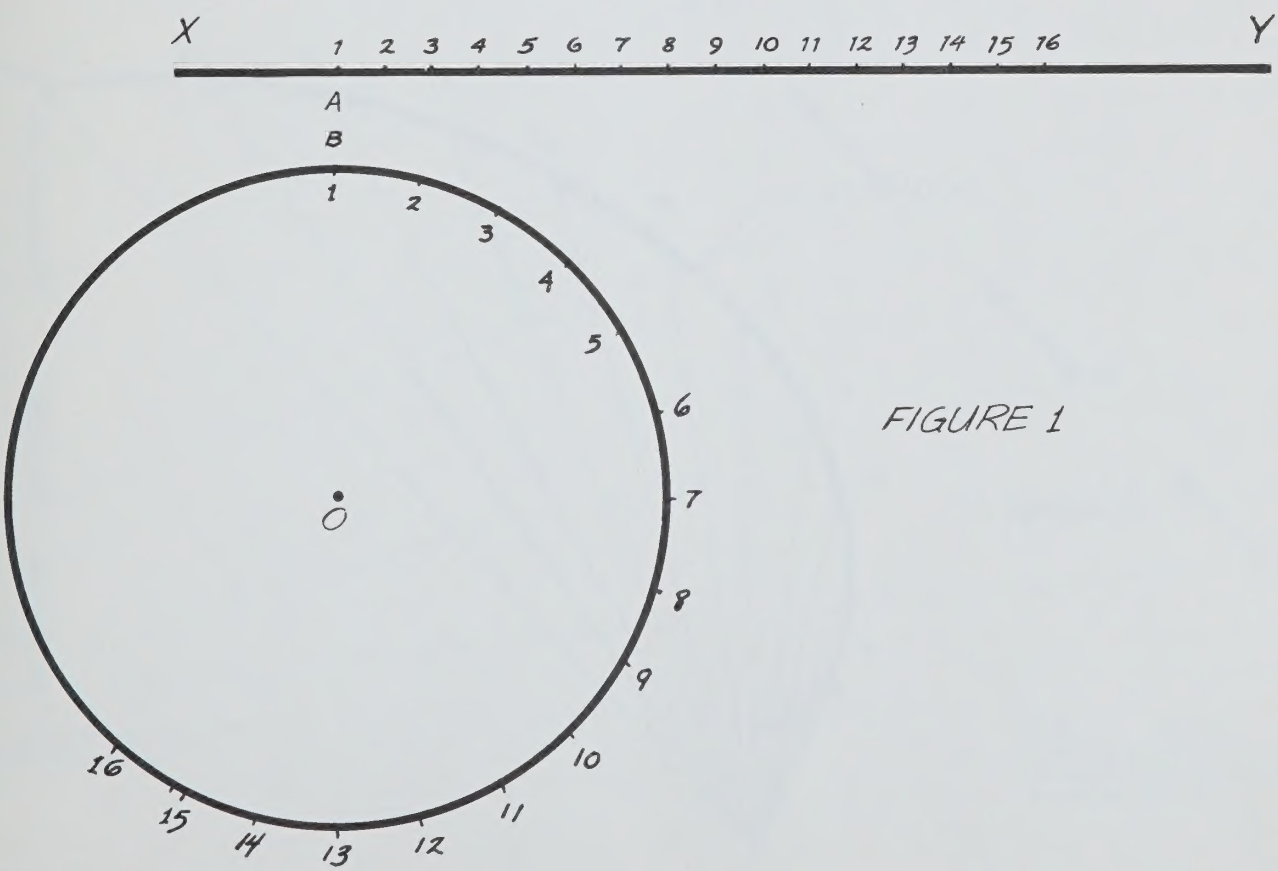


FIGURE 1

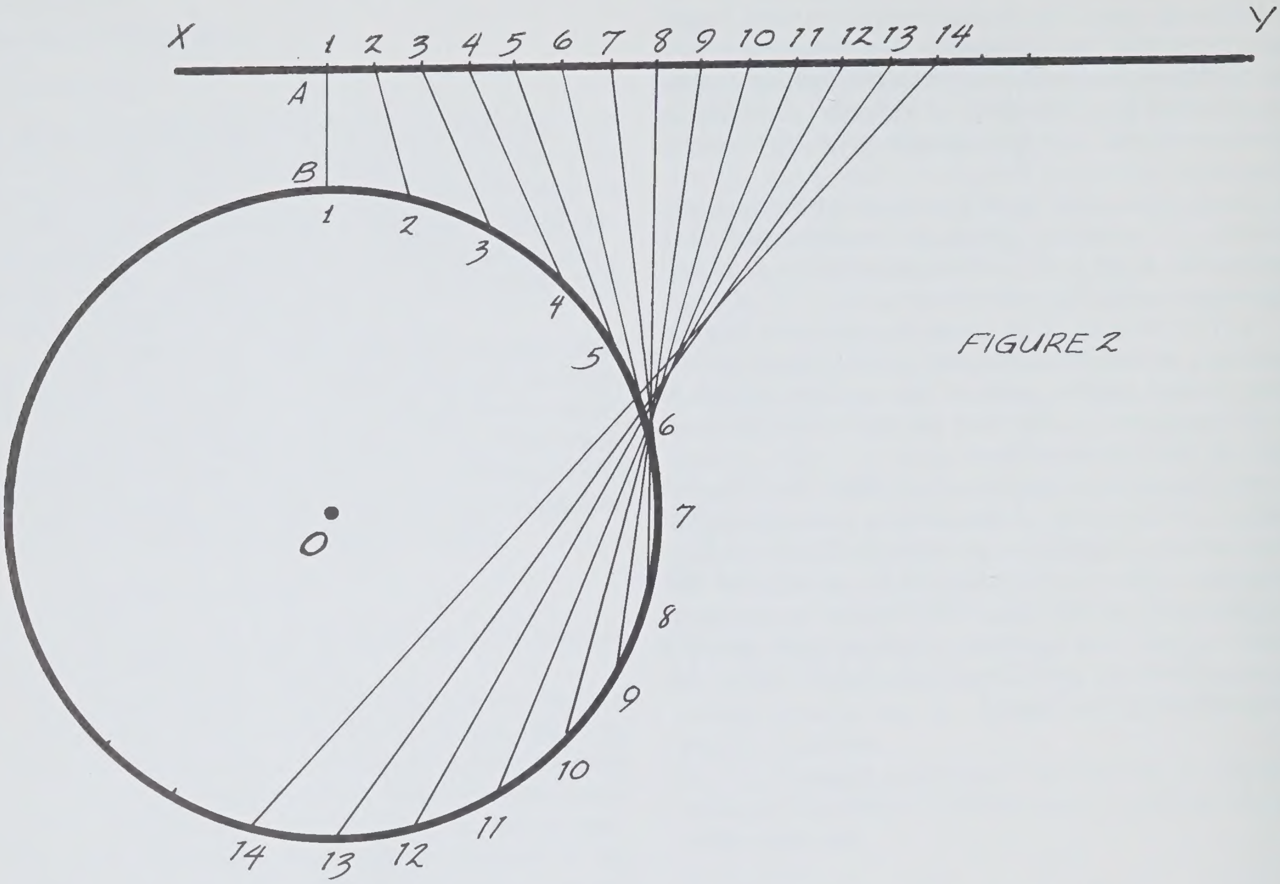


FIGURE 2

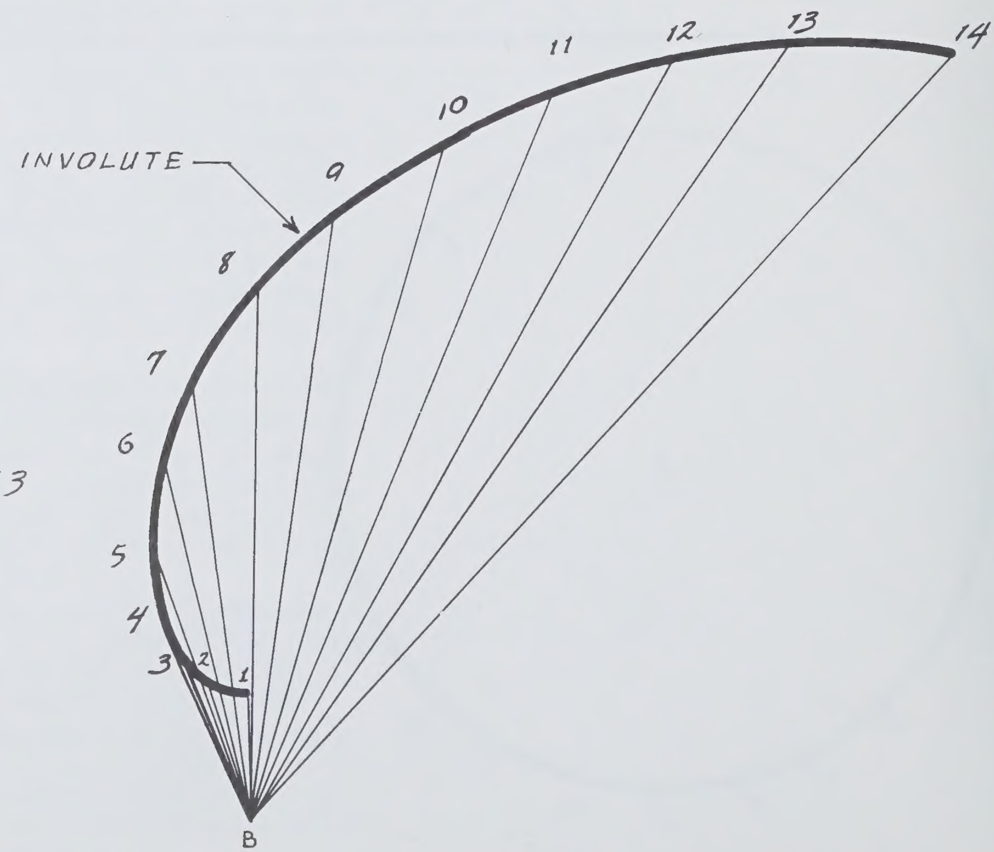
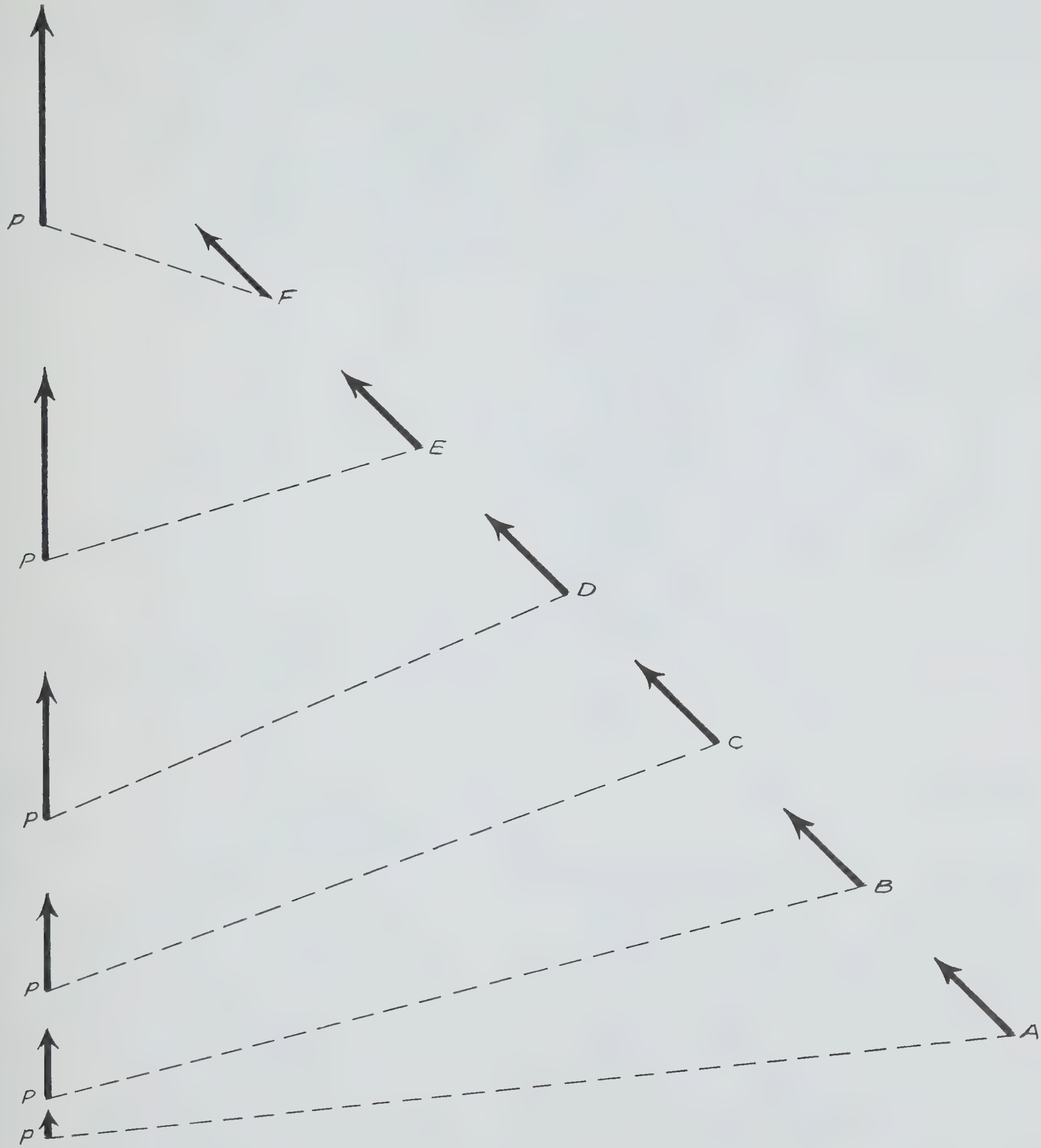


FIGURE 3

3. Another example to establish the idea of a fictitious force in an accelerated frame of reference is illustrated as follows:

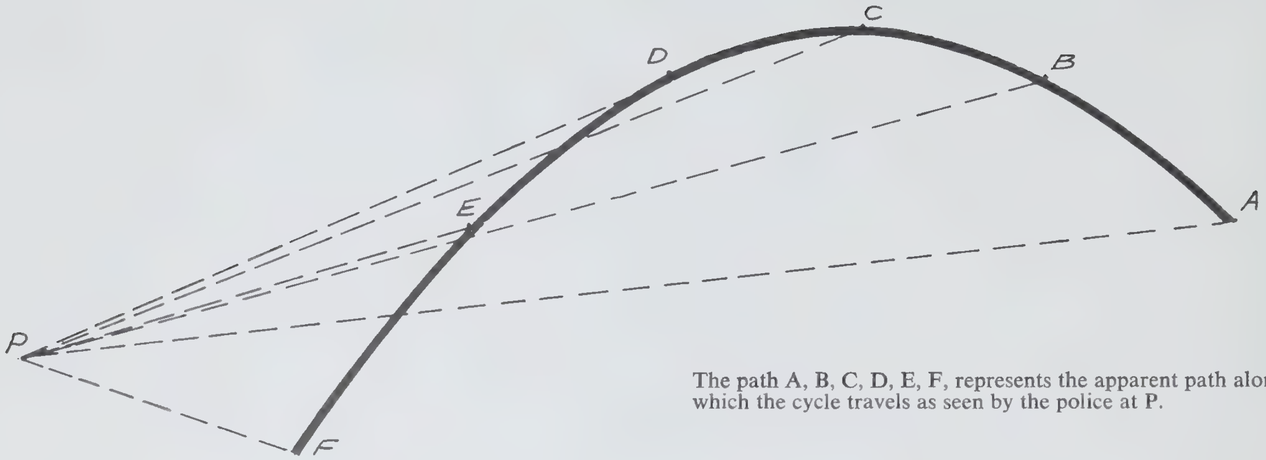


P represents police car accelerating north.

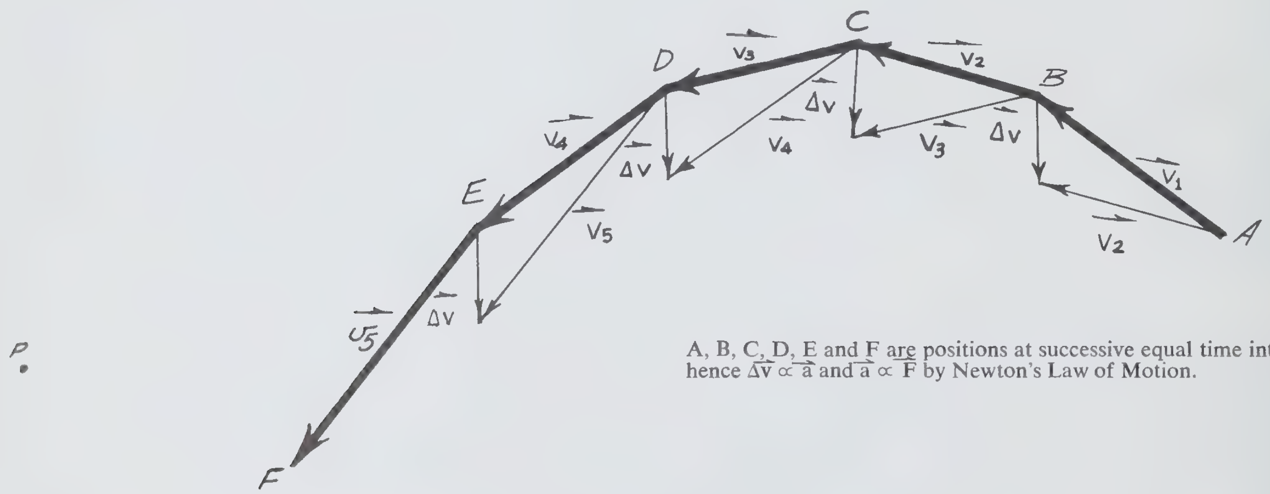
A, B, C . . . represent successive positions of a motorcycle moving northwest at constant velocity.

From 'earth' frame of reference the motorcycle is travelling with uniform velocity. How does the cycle move relative to the accelerating police car? Relative positions of cycle from police car are shown by broken lines PA, PB, PC etc.

Here the position vectors PA, PB, PC, etc. are brought to the common point of origin P.

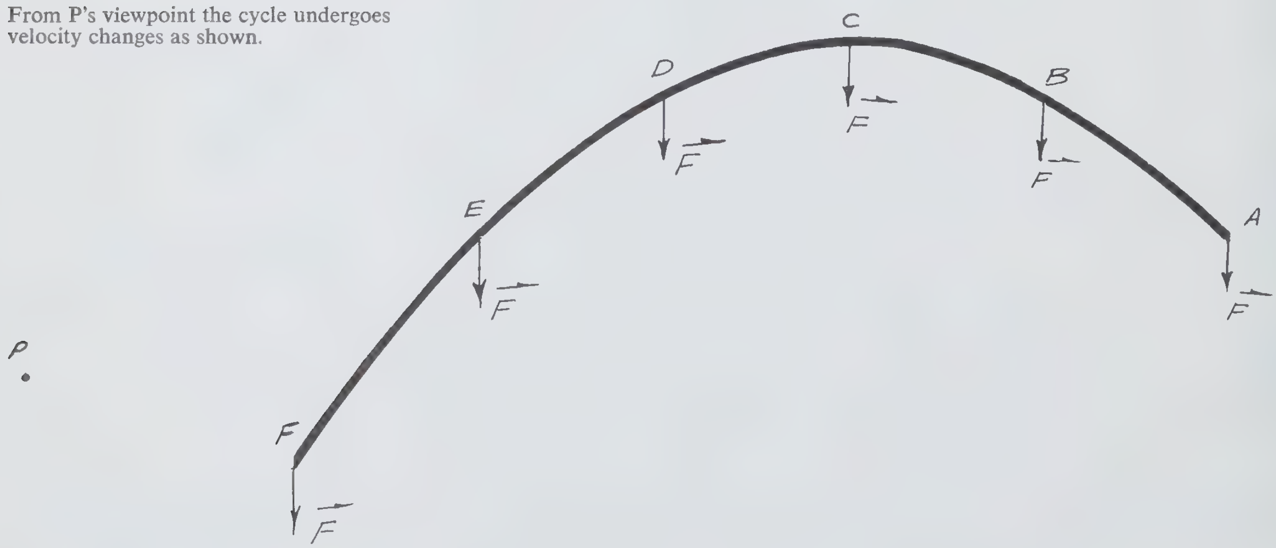


The path A, B, C, D, E, F, represents the apparent path along which the cycle travels as seen by the police at P.



A, B, C, D, E and F are positions at successive equal time intervals, hence $\vec{\Delta v} \propto \vec{a}$ and $\vec{a} \propto \vec{F}$ by Newton's Law of Motion.

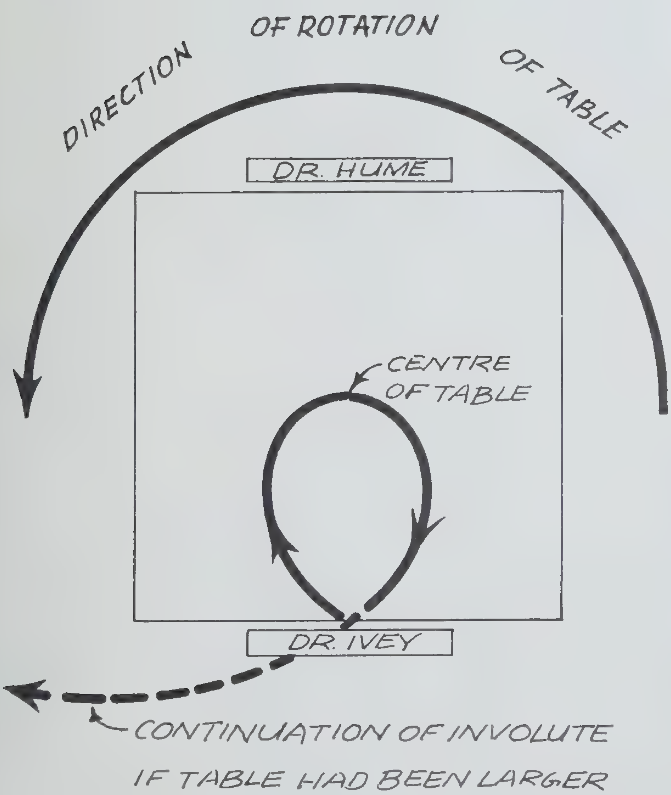
From P's viewpoint the cycle undergoes velocity changes as shown.



From P's viewpoint the cycle is acted upon by a net force $\vec{F}$ causing its apparent acceleration. This force $\vec{F}$ in the frame of reference of the police car must be a *fictitious force*. Note that it is opposite to the acceleration of the police car in the earth frame of reference.

4. It should be established with some emphasis that centrifugal force is the only fictitious force acting in a body in a rotating frame when, and *only when,* the body has no radial motion in this frame. When a body *does* have radial motion, that is, when its distance from the centre of rotation is changing (as illustrated in the film), an *additional* fictitious force called the *coriolis force* must be introduced. The net effect of these two fictitious forces is to cause the object to move in an involute.

When Dr. Ivey, in the film, launched the puck so that it returned to him after half a revolution, the puck was also following an involute. So that this might happen, the puck had to be given the correct speed in the correct direction. The path in the rotating frame of reference would appear as follows:

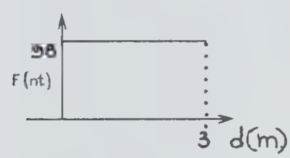


Program 12
Energy and Work

This program relates to chapters 23 and 24 of the PSSC text (2nd ed.). Its main purpose is to present experimental evidence for the fact that work as measured by Force $\times$ distance and hence by the area under a Force-distance curve does measure the transfer of kinetic energy to a body. The force in this case is the *net* force since it is only the *kinetic energy* gained by the body which is measured after the work is done. However, friction is kept to a minimum so that the net force is as nearly equal to the applied force as possible. The lesson is presented in the PSSC film *Energy and Work* with Prof. Dorothy Montgomery of Hollins College, Virginia.

MAJOR POINTS OF THE PROGRAM

1. The film opens with several examples of energy being transferred from one body to another. We are then reminded that whenever work is done, energy is transferred. The amount of work is the amount of energy transferred.
2. A large scale falling-ball experiment is the first one used to provide experimental evidence for the above statement. The work done by the gravitational field of the earth on the falling ball is compared with the kinetic energy gained by the ball. In connection with the experiment, notice should be taken of the following points:
a) The force on the ball is constant in this case (98 newtons).
b) The work done on the ball equals the area under the force-distance curve



$98 \times 3 = 294$
(nt. $\times$ m = joules)

c) The instantaneous velocity of the ball exactly at the 300 cm. mark should be used in the formula $\frac{1}{2}mv^2$ for finding its gain in kinetic energy. The velocity Prof. Montgomery uses is found by measuring the time it takes the ball to fall through the last 15 cm. of the total distance (3 m.). This is a case of using the average velocity over a small interval as an approximation to the instantaneous velocity (see discussion below).
3. The energy was put into the earth-ball system in the first place by using the 'muscle energy' of the man who pulled the ball up the 3 metres. The energy put into this system is called *potential energy.* It is also measured by the work done.
4. Potential energy can be stored in *any system* of interacting masses and the energy can be returned to the masses in the form of kinetic energy with *any* kind of force *as long as the force depends only on the separation* between the masses.

5. An experiment to illustrate the above statement for a force *which is not constant* is then shown. The following points should be noted in connection with this experiment:

a) The potential energy is in the form of elastic energy in a stretched spring and is again gained from 'muscle' energy.

b) The calibration of the 'black box' used to draw the force-distance curve is checked before it is used.

c) There is a little friction in the machine and hence when Prof. Montgomery is stretching the spring, the force exerted on the gauge equals the force of the spring plus friction, whereas on the return the force on the gauge equals the force of the spring minus friction. Ideally, there should be no friction if we are to say that whether we are putting energy into the system or taking it out, the mechanical energy transferred is the same. When it is said that "a little energy rubbed off here", it is meant that a little mechanical energy was 'lost' in the form of heat energy.

6. Note that the total of all the individual energy transformations taking place in the Rube Goldberg machine is asked for.

7. To introduce the idea of conservation of energy, a thermocouple meter is attached to the spike to show that the kinetic energy of the ball has gone into heat.

POINTS FOR FURTHER DISCUSSION AND AMPLIFICATION

1. In the falling-ball experiment, the velocity obtained by measuring the average velocity over the last 15 cm. of the drop is in error by close to 2½%. This can be seen as follows. 15 cm. is 5% of the total drop of 300 cm. Because there is uniform acceleration, the average velocity over the interval equals the instantaneous velocity at the middle of the time interval of 20 milliseconds. Since the interval is so short, the instantaneous velocity at mid-time is *very* nearly the same as the instantaneous velocity at the middle of the distance interval. The middle of this 15 cm. interval is therefore 7.5 cm. above the bottom and therefore the K.E. calculated at this point is 2½% less than the K.E. at the end of the 300 cm. drop.

2. Although the K.E. gained by the earth is negligible compared to the K.E. gained by the ball (see section 24-3 of the text), the students should remember that its gain in *momentum* is equal and opposite to that of the ball.

3. When the variable-force machine transferred energy to the cart it also transferred some rotational kinetic energy to the pulley wheel. The wheel was made of wood and holes were drilled in it to reduce its mass and hence minimize this effect.

4. In plotting the force, care was taken to pull the force indicator at constant speed. This was necessary to ensure that balanced forces acted on the gauge at all times and therefore the force exerted by the machine is equal and opposite to that exerted by Prof. Montgomery. If there was any acceleration, we would of course be creating kinetic energy in the force indicator as well as potential energy in the spring, and then our results with the cart would be badly in error.

5. The answer to the first question in the program is that we can use the area under a force-distance curve to calculate work done only when the force is always in the direction of motion.

Program 13
Elastic Collisions and Stored Energy

INTRODUCTION

This program teaches the properties of an elastic collision by examining, in detail, the interaction of two colliding dry ice pucks. By measuring the kinetic energy of each puck at every stage of the collision, one is led to the concept of stored or potential energy. This program relates directly to sections 23-5 through 23-8 of the PSSC textbook (new ed.). The viewing of this telecast will be helpful in the study of sections 24-1, 24-3 to 24-6, and of 28-7. An acquaintance with the properties of elastic and inelastic collisions is also needed for the study of Chapter 34 in connection with the Franck-Hertz experiment.

MAIN POINTS OF THE PROGRAM

1. The program begins with a very complicated inelastic collision in which the earth is one of the bodies involved. Kinetic energy disappears.
2. When a player bats a ball, the earth is again one of the bodies involved in the collision. The situation is still too complicated to be analyzed.
3. Frictionless, dry ice pucks on a horizontal surface are used in the program as colliding bodies. These form a system which is isolated from the earth. Collisions between these pucks when a lump of putty is placed between them, or when metal hits metal, again show a loss of kinetic energy in the system as a whole. It is stated that the lost kinetic energy went into heating the putty or the metal.
4. In the next situation, two tall cylindrical pucks are used, each of which contains a magnet. This is demonstrated by showing that they can either attract or repel each other.
5. A head-on collision between these pucks shows that the kinetic energy before collision is equal to the kinetic energy after collision. This kind of collision is an *elastic* collision in contrast to the inelastic type where kinetic energy is permanently lost to the colliding bodies. However in *both types* of collision, *momentum is conserved.*
6. To study exactly how kinetic energy is transferred from one object to another in an elastic collision, the kinetic energy of each is measured at various times throughout the collision.
7. The kinetic energy is calculated from a strobe picture showing the positions of the pucks at regular time intervals. The displacement (Δd) in the equal time intervals is measured. The kinetic energy is calculated in the following way:

$$E_K = \tfrac{1}{2} mv^2$$

$$\text{but } v = \frac{\Delta d}{\Delta t}$$

$$\therefore v^2 = \frac{(\Delta d)^2}{(\Delta t)^2}$$

$$\text{Substituting, } E_K = \tfrac{1}{2} m \frac{(\Delta d)^2}{(\Delta t)^2}$$

but m and Δt were constant throughout the collision,

therefore $E_K =$ (a constant) $\times (\Delta d)^2$

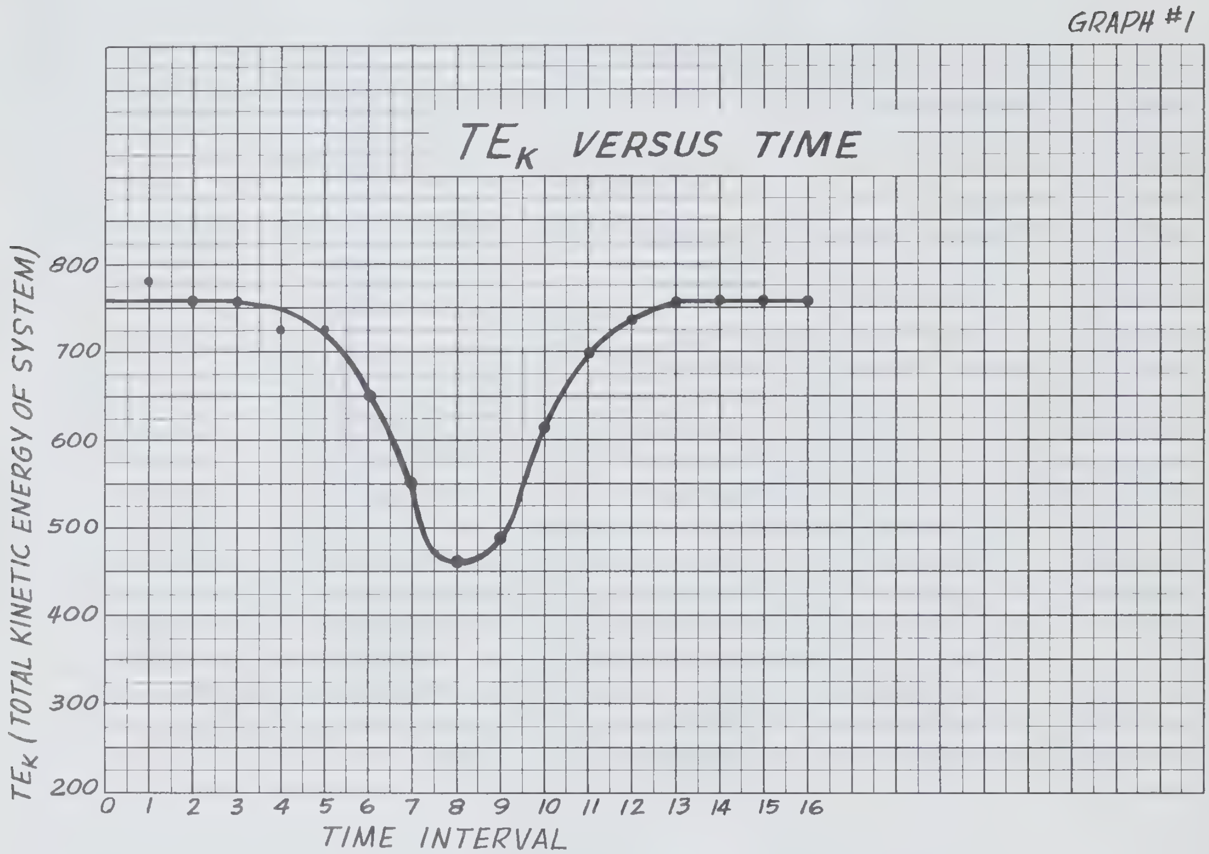
$\therefore E_K \propto (\Delta d)^2$

Therefore, any change in $(\Delta d)^2$ causes a corresponding change in E_K, and therefore, $(\Delta d)^2$ is used as a relative measurement of E_K in all the calculations. Since the pucks have equal masses, one only needs measurements of $(\Delta d)^2$ to compare the kinetic energies of the two pucks.
8. The following table is then derived:

Time Interval	Δd_1	Δd_2	$E_{K1}=(\Delta d_1)^2$	$E_{K2}=(\Delta d_2)^2$	TE_K	S
1	28.0	—	784	—	784	208.5
2	27.5	—	756	—	756	180.5
3	27.5	—	756	—	756	153.0
4	27.0	—	729	—	729	126.5
5	27.0	—	729	—	729	100.0
6	25.5	?	650	?	650	77.0
7	23.0	5.0	529	25	554	57.5
8	19.0	10.0	361	100	461	47.0
9	15.5	16.0	240	256	496	51.0
10	15.5	19.5	240	380	620	67.0
11	15.5	21.5	240	462	702	90.0
12	16.0	22.0	256	484	740	116.0
13	16.0	22.5	256	506	762	143.5
14	16.0	22.5	256	506	762	171.5
15	16.0	22.5	256	506	762	200.0
16	16.0	22.5	256	506	762	228.5

9. A graph of TE_K versus time is shown (see graph #1) and the significant features are discussed. The concept of stored energy is then introduced.

10. The separation of the pucks at regular time intervals is measured and a graph of TE_K versus separation is plotted (see graph #2). From this it is observed that the stored energy (or lost K.E.) depends only on the separation.

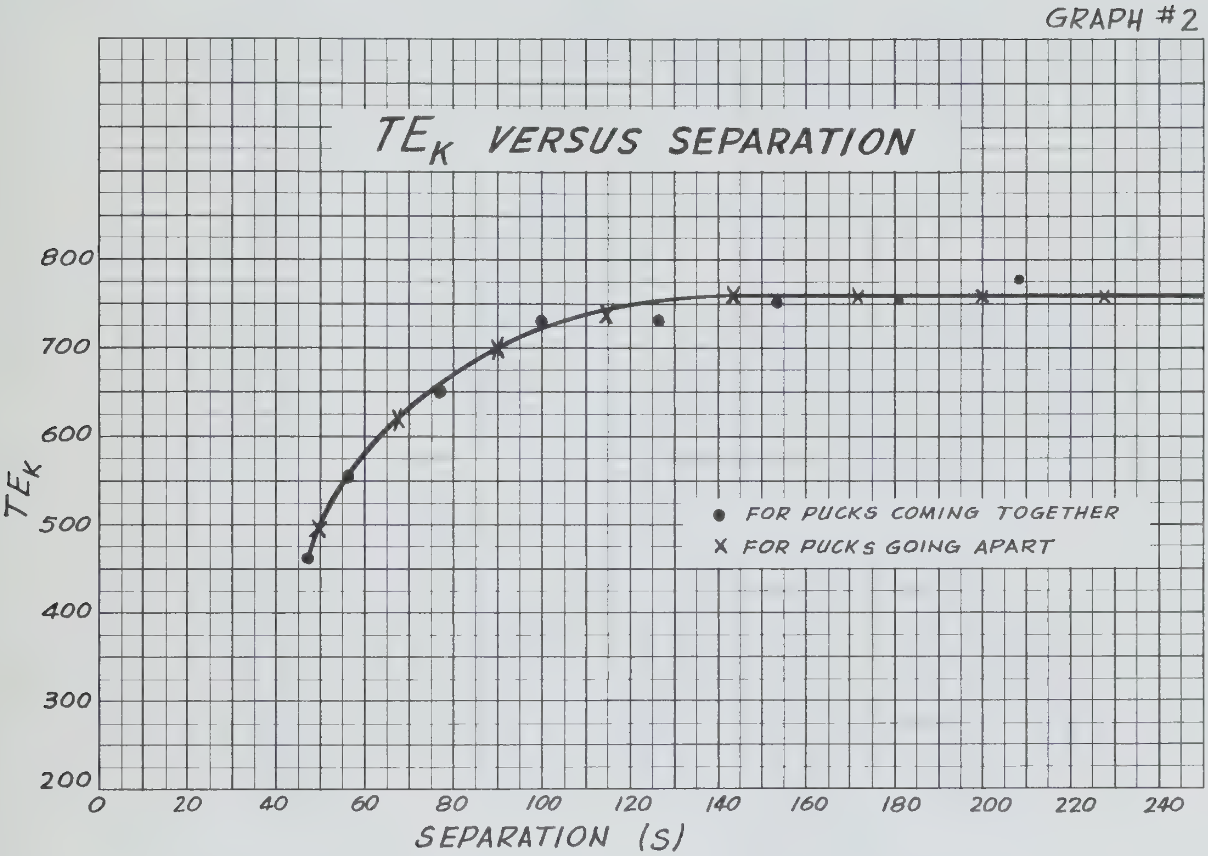


11. A graph of stored energy versus separation is then plotted (see graph #3, solid line). Other collisions are tried, and in every case, the stored energy follows the same relationship to separation between the pucks.

12. To prove that the stored energy is completely capable of being recovered, independent of the *time* that it is stored, two pucks are tied together with a string. The string is then burned, releasing the pucks. They both gain kinetic energy. The total kinetic energy is calculated and plotted on the same axes as stored energy versus separation. (See graph #3, dotted line).

The pucks started with a separation of 56.5 mm and possess a certain amount of stored energy. They should have this amount of kinetic energy when released. The experiment confirms this to be true. This illustrates that an elastic collision was taking place between the pucks and that the stored energy depends *only* on the separation.

13. The sum of the kinetic and potential energies in a system is called the *total mechanical energy* of the system. A study of graph #3 shows that another way of describing the property of an elastic collision is to say that the total mechanical energy is a constant or is conserved.



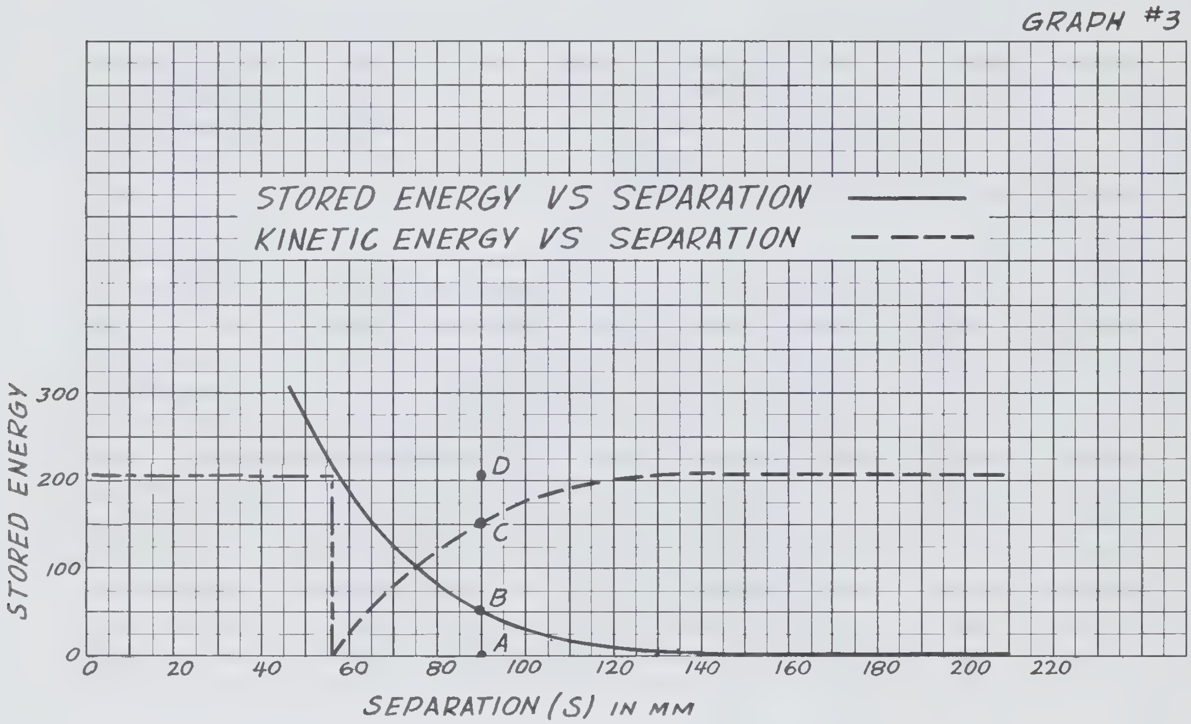
14. The statement that stored energy depends only on the separation of the bodies is exactly equivalent to the statement in the text that the force of interaction between the colliding bodies depends only on the separation for an elastic collision.

15. The students are urged to analyze one of the collisions for themselves. The work sheets on these are available from either Stark Electronics, Ajax, Ont. or from Canadian Laboratory Supplies Ltd., 80 Jutland Road, Toronto (work sheets: stroboscopic photographs of elastic collision).

POINTS FOR DISCUSSION

1. The initial loss in energy of the incident puck during the first few time intervals before the target puck started to move is a result of the puck scraping the table top. This is easily understood if one considers that the cylindrical puck is very top heavy. Furthermore, as it is floating on a very thin layer of gas, it would be almost impossible to push it so that it would not wobble at all. When it leans forward and backward the puck scrapes on the table top, causing the irregular loss in kinetic energy before the collision starts.

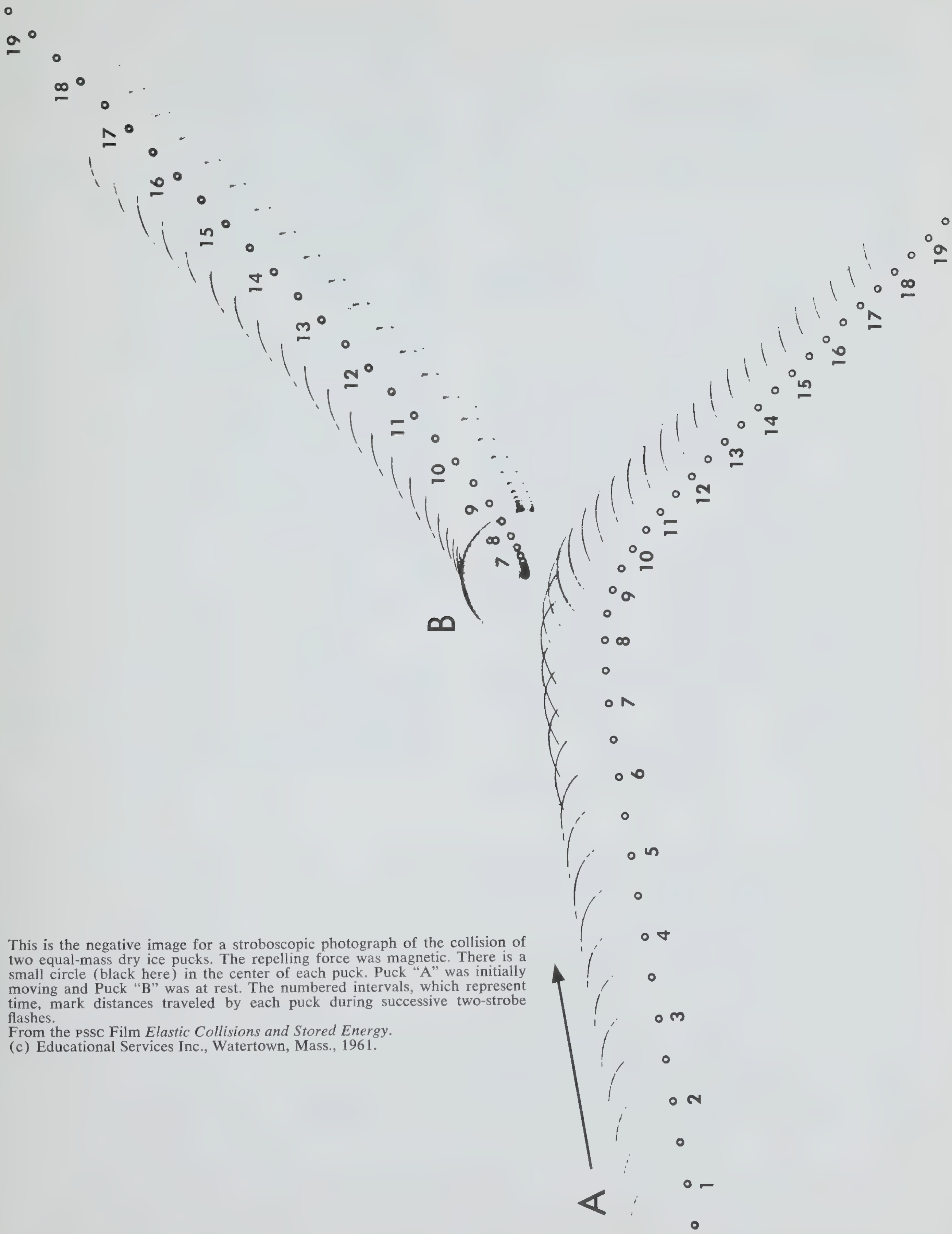
3. In case any student asks what type of function exists between force and separation, point out that it cannot be an inverse square relationship because of the two poles in each magnet. It is more likely an inverse cube law. It is of interest then to compare the function of the potential energy versus separation for the magnets (see graph #3) with that for a mass on the end of a string (fig. 24-4 PSSC textbook) or for two equal charges (fig. 28-13, PSSC textbook).



2. This program is particularly useful as an addition to the text because it illustrates the fact of "force of interaction depending only on separation" for an elastic collision in which the interacting force is a rather complicated function of separation. This is in contrast to the simple 'step function' of force versus separation used in the initial development in the text.

4. The usefulness of the potential energy concept in studying collisions should be emphasized. There is a gravitational potential energy associated with any two masses and an electrical potential energy associated with any two charged particles. If the collisions are elastic, we can use the laws of conservation of momentum and of kinetic energy to solve problems involving two bodies where the forces of interaction are *not known* (an example of this is the discovery of the neutron by Chadwick as outlined on p. 399 of the textbook, First edition).

Even for inelastic collisions, the concept of potential energy is useful as long as one can predict the work done by the bodies (or by us on the bodies) as the separation of the bodies changes.



This is the negative image for a stroboscopic photograph of the collision of two equal-mass dry ice pucks. The repelling force was magnetic. There is a small circle (black here) in the center of each puck. Puck "A" was initially moving and Puck "B" was at rest. The numbered intervals, which represent time, mark distances traveled by each puck during successive two-strobe flashes.
From the PSSC Film *Elastic Collisions and Stored Energy*.
(c) Educational Services Inc., Watertown, Mass., 1961.

Program 14
Mechanical and Thermal Energy

INTRODUCTION

This program demonstrates the transfer of kinetic energy of orderly bulk motion to the kinetic energy of random molecular motion (thermal energy). This explains what happens to the 'lost' kinetic energy in an inelastic collision and illustrates what was meant by 'heat' in Section 23-10 of the textbook.

The program also relates directly to Sections 25-1, 2, 3 and 5 of the PSSC textbook (second ed.).

Although Chapter 25 is not part of the required course this year, it was felt that this material is very worthwhile as enrichment for the interested student. It is hoped that all students will at least read Chapter 25.

MAJOR POINTS OF THE PROGRAM

1. While observing the transfer of potential energy to kinetic energy in the case of a bouncing ball, it is seen that a loss of orderly mechanical energy is taking place. The question of where this energy went is then raised. It is suggested that the molecules of the air and also of the surface gained this energy.
2. To understand the loss of energy to the air, a model showing the behaviour of gas molecules is demonstrated. The purpose of the demonstration with this 'marble machine' is to emphasize that in our study of a gas, we cannot study the behaviour of individual molecules, but must be satisfied with values of average behaviour such as measurements of pressure and temperature.
3. Temperature is explained to be the average kinetic energy of linear motion of molecules. The train of reasoning by which this is established, is as follows:

The pressure of a gas is a result of the collisions of the molecules with the walls of the container.

Pressure $\propto$ the momentum mv, and the speed v of the molecules.

Therefore, pressure $\propto$ mv^2

Therefore, pressure $\propto$ average kinetic energy of the centre of mass motion of molecules.

An experiment is then performed to show that the pressure of a gas in a container $\propto$ its temperature.

Two different gases are used to indicate that all gases behave alike, at least in the range of temperatures from that of dry ice and alcohol to boiling water. By plotting a graph of pressure versus temperature, it is shown how the absolute temperature scale is derived. Since from this experiment $P \propto T$ and from the previous reasoning $P \propto mv^2$, it is concluded that $T \propto mv^2$ and hence we say that temperature is a measure of average kinetic energy of linear motion of the molecules.

4. Returning to the original question of how the bouncing ball lost energy to the gas, Prof. Zacharias, in the film, illustrates the collisions between a ball and gas molecules by means of a model. In it we see the orderly kinetic energy of a dry ice disc (representing the ball) being lost and given to the random kinetic energy of small steel balls (representing gas molecules).
5. Prof. Zacharias then returns to the marble machine to demonstrate the mechanism of thermal conduction.
6. The Principle of Conservation of Energy is stated.
7. Various methods by which energy may be transported are discussed, and some are illustrated.

ADDITIONAL DISCUSSION

1. The program is *not* intended to teach the law of conservation of energy. It cannot do so because no measurements are made at any stage of the program. It simply illustrates, with the aid of models, how mechanical energy is converted into thermal energy.
2. When Prof. Zacharias makes the statement, "but with enough molecules, this chaotic motion takes on a certain order", what is understood is that with a large enough number of molecules, the average behaviour of the random motion becomes predictable. That is to say, the random fluctuations caused by having only a few molecules smooth out to be unobservable with sufficient molecules, and we then measure only the gross properties of the gas. It is *not* meant that the motion of the molecules becomes orderly.
3. A 'Brownian Movement Halt' indicates that the disc loses its orderly forward motion and comes to a condition where it jiggles around in a random manner under the influence of molecular bombardment. A student might ask why the object comes to a halt at all. This can easily be seen once he realizes that as the body is moving forward, the average bombardment on the front will exceed that from the rear, thus opposing the motion of the body.

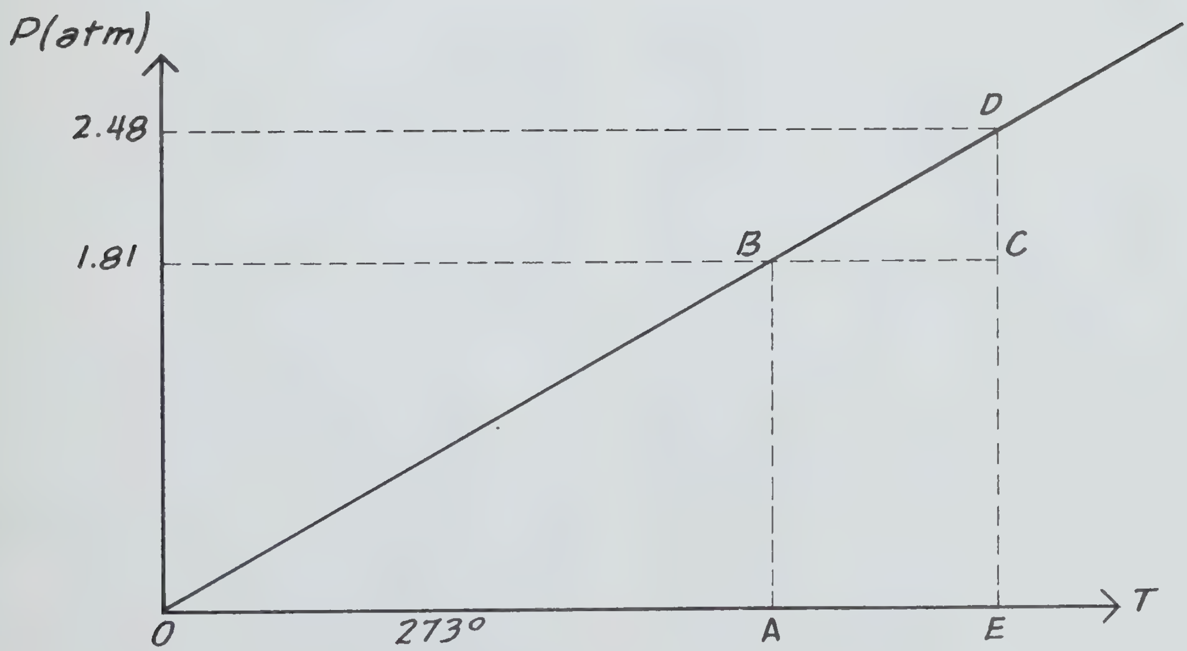
4. It is interesting to note the method used by Prof. Zacharias for setting the Kelvin Temperature Scale. The data from the program is shown on the following graph. 1.81 (atm.) was the pressure at the temperature of melting ice. 2.48 (atm.) was the pressure at the temperature of boiling water. Prof. Zacharias started by *choosing* the temperature of melting ice to be 273°. He then plotted the point B, joined OB, and produced the straight line. Point D was then located on this line opposite 2.48 atm. and DCE constructed. Then, by comparing the similar triangles OAB and BCD, he found that BC (or AE) represented 100 units of Temperature.

This is the reverse of the usual method in which we choose 100 units of temperature to be between the melting point and the boiling point of water (i.e. we construct the centigrade scale), plot points B and D and then extrapolate backwards to zero pressure and find that the line meets the temperature axis at 273 units below the temperature of melting ice.

5. Other pieces of experimental evidence in support of a kinetic theory of matter besides Brownian motion are:

a) the natural noise generated within an electrical system

b) the velocity of sound in a medium is about the same as the average speed of the molecules in the medium.



Program 15
Coulomb's Law

INTRODUCTION

This program introduces a quantitative study of the force law existing between electric charges. It makes use of the PSSC film, *Coulomb's Law*, with Prof. Eric Rogers of Princeton University. It relates directly to Section 27-1 through 27-3 of the textbook and laboratory experiment IV-3.

MAJOR POINTS OF INTEREST IN THE PROGRAM

1. Demonstrations showing the importance of electrical forces in nature and giving a rough idea of their magnitude.
2. Demonstrations recalling qualitative facts about the forces between electric charges.
3. Prof. Rogers states that Coulomb's Law says "Force varies inversely as the square of the distance between the charges" and then emphasizes the meaning of an inverse-square law by an intriguing illustration.
4. A diagram of Coulomb's original apparatus is shown.
5. Prof. Rogers explains the operation of the spring balance type of apparatus which he is going to use in his experiments. He shows that each division on the scale represents a force of 1/10,000 of a newton, and therefore he will be able to estimate the force to within roughly 1/100,000 of a newton.
6. The experiment investigating the relationship between force and distance between two charged spheres is performed. The experimental data is as follows:

Dist. (d)	Force (x 10^{-4} newtons)	$\frac{1}{d^2}$	$F \times d^2$	
1 span	23.7	1	23.7	roughly a constant
2 spans	5.4	¼	22	
3 spans	2.5	1/9	22.5	

The experimental results confirm that the force varies inversely as the square of the distance. The generality of this law is then emphasized.

7. An experiment is performed to investigate the effect on the force of changing the quantity of charge on the spheres while keeping the distance the same. It should be noted that the charge on a ball is reduced to one half of its original value by the technique of touching it to another neutral ball of the same size so that the original charge is shared equally between the two balls. The experiment shows that the force is proportional to the quantity of the charge on each of the spheres, within the limits of experimental error.
8. Prof. Rogers pointed out that good scientists often formulate general laws on rather poor evidence but that this is fine as long as the result is then rigorously tested. He then goes on to devise a very sensitive test of the inverse-square law for electrical point charges. He reasons from an assumption that the inverse-square law is correct and, from the geometry of a sphere, that there must be no net force on a test charge placed anywhere inside a charged hollow metallic sphere. This prediction is then tested experimentally.
9. Another test is performed to show the need for a completely closed conducting surface around the test charge.
10. It is then stated that the result holds for any closed conducting surface even though there may be many holes in the surface. This is demonstrated by means of a huge wire cage.

ADDITIONAL POINTS FOR DISCUSSION

1. It will be recognized that the 'ancient charging device' used by Prof. Rogers is the electrophorus. It is suggested that you take this opportunity to review charging by induction as discussed in Section 26-5 of the PSSC textbook (second ed.).
2. The students should realize that it is not possible by means of the electrophorus to recharge the spheres with the same quantity of charge each time. Consequently, in the investigation of the inverse-square law between force and distance when the charge was constant, it was necessary to work quickly because there is always some leakage of charge from the metal spheres.
3. The technique of designing an apparatus which gives a zero reading as the correct result, when testing a physical law or making a measurement, is one which is frequently used when doing very precise experimentation (e.g. the null point when using a bridge circuit to measure resistance, capacitance, etc.). As is pointed out in the PSCC Teacher's Guide, since the exponent 2 in $1/r^2$ is known to one part in 10^9, it is obvious that no direct measurement of force could produce such accuracy.
4. In a part of the film which it was not possible to use in the program, Prof. Rogers asks the question, "What would gravity be like inside a hollow earth?" Since gravity also obeys an inverse-square law, the gravitational force would be zero at any point inside an earth which was a hollow spherical shell. However, for gravity the null result would only be obtained with a *spherical* body whereas for electrical forces the null result is obtained inside a conductor of *any* shape. This occurs because electrons are free to move in a conductor and will always arrange themselves on the surface of the hollow closed conductor until the force on a charge inside is zero.
5. The inverse-square law is strictly true only for point charges or when the charge is distributed evenly over the surface of a sphere. Two charged metal spheres do not obey an inverse-square law exactly, due to the effect of induced charges on each other. However, as long as the distance between them is several times their diameter, the effects of uneven distribution of charge due to induction may be ignored and the inverse-square relationship may be demonstrated quite well.
6. Page 28-4 in the PSSC Teacher's Guide (first ed.) gives more information on charge sharing and also some excellent quiz questions.

Program 16
The Millikan Experiment

INTRODUCTION

This program presents the PSSC film, *Millikan Experiment.* The film features Prof. Francis L. Friedman, M.I.T., and Dr. Alfred Redfield, International Business Machines. A modern version of the famous Millikan Oil Drop Experiment is demonstrated in this film section of the program. The purpose of the experiment is to show that charge comes in multiples of a natural unit.

This broadcast will help greatly in the teaching of sections 27-4 and 27-5 of the PSSC text (second ed.).

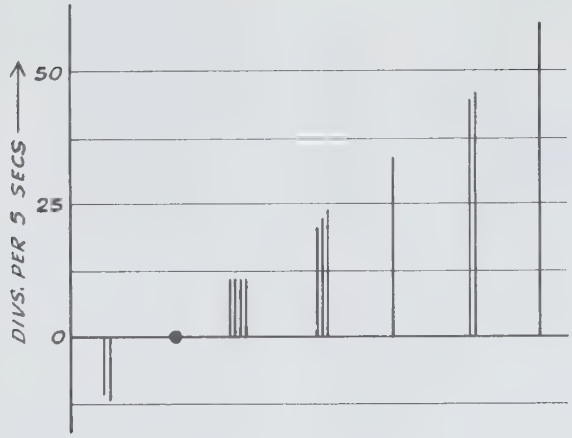
MAIN IDEAS PRESENTED IN THIS BROADCAST

1. The idea that there is a natural smallest unit of charge, or that charge comes in grains which are the same size *electrically.*
2. If charge comes in grains, then the force on an object in an electric field carrying one grain should be a certain amount, and for two grains should be twice this, and for three grains three times this and so on.
3. The broadcast presents a description of the apparatus used to produce the electric field, and the method of putting into the electric field tiny plastic spheres which carry the grains of charge.
4. The plastic spheres are viewed through a microscope. It should be noted that the distance between the parallel plates is 3.1 mm., but the whole field of view of the microscope is only a little over 1 mm.
5. Some plastic spheres are placed between the plates. The spheres fall at a steady velocity when pulled by gravity. When the plates are charged, some particles go up and some down. When the charge is reversed on the plates, the particles which were falling now rise, and the ones which were rising now fall. This shows that there are different charges on the different spheres. It is also important to notice that each particle moves at its own constant speed.
6. A particle reaches its steady speed almost instantly when the electric field is turned on or off (actually in 10^{-5} seconds). We therefore ignore the time it was accelerating when measuring the speeds.
7. Standard plastic spheres each 1.8×10^{-6} m. in diameter and 2.8×10^{-14} newtons in weight are used to carry the charges so that any differences in speed between different particles are due solely to different amounts of charge on them.
8. When three batteries are connected across the plates, a sphere carrying a certain unknown quantity of charge is kept in balance. The amount of charge *on the plates* is called the 'set charge'. The particle can be held in balance at any position over the whole field of view. This establishes the fact that there is a uniform electric field between the parallel plates.
9. An extra charge is added to the plates to pull the sphere up again.
10. The method of measuring different quantities of charge on the sphere is then discussed. At the start there is a certain quantity of charge on the sphere. When the plates have on them the set charge (provided by three 90v batteries), the electric force on the sphere upwards just balances the gravitational force downwards. The speed of the sphere is zero. When gravity alone acts, the sphere falls 23 or 24 divisions in 5 secs. (Note that the first tick marks zero time and therefore six ticks must be heard to make 5 secs.). The set charge on the plates is then reversed so that now the downward force on the sphere is the force of set charge plus the force of gravity. But since the force of set charge equals the force of gravity, the downwards force is now 2 x force of gravity. It is observed that the particle now moves 48 divs. in 5 secs. or twice the speed obtained with 1 x force of gravity. The conclusion is drawn that the speed is directly proportional to the force and therefore, by comparing speeds, we can measure the force on the sphere. Any change in charge on the sphere will cause a different force to be exerted on it by the set charge. This will become evident by the sphere not being in balance with the set charge on the plates, but moving at a speed proportional to the new unbalanced force which is called the 'driving force'. The sphere moves at constant speed because the driving force is always balanced by the force of friction of the air *within 10^{-5} secs.* after the sphere starts moving.
11. The charge on the sphere is changed by ionizing the air near it or knocking charge off it by means of X-rays. With the first burst of X-rays the charge on the sphere was changed so that with the set charge on the plates, it moved up at a speed of 12 divs. in 5 secs. This was repeated many times, that is, changing the charge and measuring the speed. The data from the film segment is reproduced below. The speeds are in number of divs. per 5 secs.

The integers to the right are multiples of the lowest speed:

$V_1 = 12$	1	$V_9 = 0$	0
$V_2 = 22$	2	$V_{10} = 23$	2
$V_3 = 46$	4	$V_{11} = 60$	5
$V_4 = 34$	3	$V_{12} = 47$	4
$V_5 = 13$	1	$V_{13} = 24$	2
$V_6 = 11$	1	$V_{14} = 11$	1
$V_7 = -12$	-1	$V_{15} =$ lost	
$V_8 = -13$	-1		

The graph of this data from the film is reproduced on the following page:



From this data, one may reason as follows:

a) All speeds are multiples of 11.8 div./5 secs.

b) The charges come on or off the sphere in natural units.

c) Since the speed under gravity alone was 23.5 div./5 secs. and since the set charge balanced the sphere against gravity at the start of the experiment, the force of the set charge on the sphere when in balance, must be the force on 2 natural units of charge.

d) Therefore, the sphere had 2 natural units on it at the start.

12. Since the force of gravity on the sphere was 2.8 x 10^{-14} newtons and since the set charge balanced this when 2 elementary charges were on the sphere, the force per elem. ch. was 1.4 x 10^{-14} newtons when three 90v batteries were connected across the plates which were 3.1 mm. apart.

13. The most important conclusion is that there is a natural unit of charge in which all charge comes. This is called the elementary charge and is the choice of the unit of charge used in finding Coulomb's Force Constant in the next program.

FURTHER POINTS FOR DISCUSSION

1. It should be emphasized that, in general, the terminal speed of a sphere moving in air is not always proportional to the force acting on it. However, in the range of speeds used in this experiment, the proportionality is accurate.

2. What this experiment has really shown is that when X-rays ionise the atoms of the plastic sphere or the gas near it, there is a natural unit charge involved. It is necessary to use other evidence to establish that this unit of charge (the electron) is the same as that involved with other interactions such as electrolysis, or other types of matter such as protons.

The neutrality of the hydrogen atom establishes that the charge on the proton is equal in magnitude, and opposite in kind, to the charge on the electron. Other evidence that there is but one elementary charge in nature is provided in succeeding PSSC films. It should be established with the students that when the sphere was pulled down with the set charge on the plate, this did not necessarily mean that the charge on the sphere was opposite in sign to that when it was pulled up. Since, in the experiment, gravity alone pulled the sphere down 23.6 divs./5 secs., therefore when it was going down 11.8 divs./5 secs. with a set charge on the plates, there must have been just one less unit of charge on the sphere than when it was balanced. Therefore, during this experiment there was the same kind of charge on the sphere at all times. When it was balanced, there were two units charged on the sphere and in trial No. 11 the sphere had five *additional* units of charge on it, making a total of seven. Students should establish how many units of charge were on the sphere for each of the other trials.

3. The experiment in this broadcast does more than establish the existence of a fundamental unit of charge. For the specific plate separation and number of batteries used, it provides a calibration of the electric force on an elementary charge in terms of a gravitational force. The force of 1.4 x 10^{-14} newtons on each elementary charge, when the plate separation is 3.1 mm. and three 90v batteries are connected across them, is used as a 'standard electric force per elementary charge' in much of the succeeding work in the PSSC course.

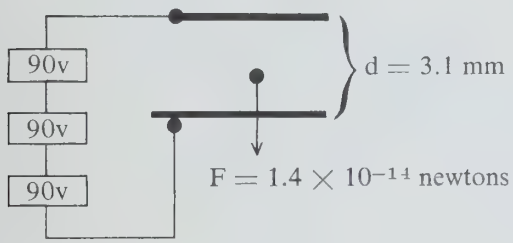
Program 17
Coulomb's Force Constant

INTRODUCTION

This program presents the material contained in 27-6 and 27-7 of the PSSC textbook (second ed.). The broadcast includes the PSSC film, *Coulomb Force Constant,* with Prof. Eric Rogers of Princeton University. The broadcast establishes how to find the value of the Coulomb Force Constant by using a large scale version of the 'Millikan apparatus' shown in the previous program.

MAJOR POINTS OF THE PROGRAM

1. We know that the force on an elementary charge is 1.4×10^{-14} newtons when it is between two parallel plates which are 3.1 mm. apart and three 90v batteries are connected across them.



2. To find k in $F = \frac{kq_1q_2}{r^2}$ we must know F, r, q_1 and q_2
where F is in newtons
r is in metres
q_1 and q_2 are in natural units of charge

In the program, Coulomb's Law is written in the form $F = \frac{k\,N_1N_2}{d^2}$ to emphasize the fact that quantity of charge is being measured in the number of elementary charges.

3. The quantity of charge on an object is established by measuring the force on it when it is placed in an electric field which exerts a force of 1.4×10^{-14} newtons per elementary charge. For example, if the force on a charged sphere between the plates was 1.4×10^{-10} newtons, the force is greater than the force on an elementary charge by a factor of 10^4 times and, therefore, there are 10^4 elementary charges in excess on the charged sphere.

4. We need larger objects than the tiny plastic spheres used in the Millikan Experiment if we wish to carry larger amounts of charge. We therefore need larger and more widely spaced plates in order to measure the force on these larger objects, and hence find the charge on them. The problem then arises as to designing a *large scale* 'Millikan apparatus' which will still exert a force of 1.4×10^{-14} newtons/(elem. ch.) on any charged object which is between the plates. By means of a 'research program', Prof. Rogers establishes that the force F on a charged object between the plates varies inversely as the distance between the plates and directly with the number of batteries connected across them. The surface area of the plates has no effect on F as long as the plates are much wider than the distance between them. Therefore, by making the large scale Millikan apparatus so that the plates are 100 times further apart (31 cm), and by using 100 times as many batteries (300 batteries or 27,000 volts), we still have a force of 1.4×10^{-14} newtons/(elem. ch.) between the plates.

5. The main experiment is then performed in the following steps:

a) Two spheres are *equally* charged;

b) The force between them is measured at a known distance using the 'Coulomb Law apparatus'. The results obtained are:

$F = 6.7 \text{ x } 10^{-4}$ newtons
$d = 15$ cm. or .15 m.

c) The sphere on the spring balance is placed between the plates of the big Millikan apparatus and the force on it is measured in order to find the values of N_1 and N_2. The charged sphere was placed exactly between the plates so that the forces due to induced charges will cancel because of symmetry. The value obtained is:

F on $N_1 = 35.5 \text{ x } 10^{-4}$ newtons
but F on 1 elem. ch. $= 1.4 \text{ x } 10^{-14}$ newtons
$\therefore$ number of elem. ch. on the sphere =

$$\frac{35.5 \text{ x } 10^{-4}}{1.4 \text{ x } 10^{-14}} = 25 \text{ x } 10^{10} = N_1$$

$\therefore N_1 = N_2 = 25 \text{ x } 10^{10}$ elem. ch.

Substituting in $\quad F = k\frac{N_1\,N_2}{d^2}$

We now have

$$6.7 \times 10^{-4} = \frac{k\,(25 \times 10^{10})^2}{(.15)^2}$$

$$6.7 \times 10^{-4} = \frac{k \times 625 \times 10^{20}}{225 \times 10^{-4}}$$

$$6.7 \times 10^{-4} = k \times 2.8 \times 10^{24}$$

$$k = \frac{6.7 \times 10^{-4}}{2.8 \times 10^{24}} = 2.4 \times 10^{28} \qquad \frac{\text{newton} - \text{m}^2}{(\text{elem. ch.})^2}$$

NOTE: In the PSSC film, Prof. Rogers does this a little differently. Also, these calculations are somewhat rough estimates and if worked out more carefully give a result of

$$k = 2.34 \times 10^{-28} \qquad \frac{\text{nt} - \text{m}^2}{(\text{elem. ch.})^2}$$

However, as Prof. Rogers states in the broadcasts, the roughness of the measurements makes any result within 10% of the accepted value a satisfactory one with the use of this apparatus.

6. The electrical force between two electrons a distance *d* apart is compared with the gravitational attraction between them.

7. The electrical attraction between a proton and an electron in the hydrogen atom is compared with the gravitational attraction.

8. There is a review of the calculation of the value of *k* using the method outlined

Program 18
Elementary Charges and the Transfer of Kinetic Energy

INTRODUCTION

This program presents a large segment of the PSSC film bearing the above title. The film features Prof. Francis L. Friedman of M.I.T. The purpose of the broadcast is to illustrate an experimental check on the assumptions made in Sections 28-1 and 28-2 of the text. The program particularly relates to Section 28.5 of the text (second ed.).

MAJOR POINTS OF INTEREST

The following points outline the development of thought in the program:

1. At the beginning of Chapter 29 of the text, the assumption is made that for a charge being accelerated from rest in the electric field between two parallel plates, the force (F) on the charge times the distance (d) between the plates, equals the kinetic energy possessed by the charge after traversing the distance (d). The main purpose of this broadcast is to illustrate an experimental check of this assumption.

2. An introduction is again made to the arrangement of parallel plates which was used in the Millikan experiment. This provides us with a known electric force of 1.4×10^{-14} newtons per elementary charge.

3. The Millikan apparatus is modified in four ways:
a) the plastic spheres are not used to carry the charges
b) the charges are provided by the emission of electrons from a hot filament
c) the plate from which the electrons leave is thin and the one they hit is a thick copper plate
d) the space between the plates is highly evacuated.

4. The total kinetic energy possessed by all the electrons passing between the plates in a given time is *predicted*. The development of this prediction is as follows:
a) the K.E. gained by one el.ch.
$= F \times d$
$= 1.4 \times 10^{-14} \times 3.1 \times 10^{-3}$ newton-m
$= 4.34 \times 10^{-17}$ joules
b) the number of el.ch. passing across in 1 sec. is measured by putting an ammeter in the circuit. A current of 2 ma or x 10^{-3} Amperes is used, but 1 Ampere $= 6.25 \times 10^{18}$ el.ch./sec.
$\therefore$ number of el.ch. passing across per sec.
$= 6.25 \times 10^{18} \times 2 \times 10^{-3}$
$= 1.25 \times 10^{16}$
c) the total energy carried across per sec.
$= 4.34 \times 10^{-17} \times 1.25 \times 10^{16}$

$$\left\{\frac{\text{joules}}{\text{el.ch.}}\right\} \left\{\frac{\text{el.ch.}}{\text{sec.}}\right\}$$

$$= 5.4 \times 10^{-1} \frac{\text{joules}}{\text{sec.}}$$

The charges, therefore, carry 5.4×10^{-1} joules per second to the thick copper plate.
d) To obtain a larger total amount of energy, the current is allowed to run for 20.5 secs.
$\therefore$ the total energy carried by the charges to the thick copper plate during one run is

$$5.4 \times 10^{-1} \times 20.5 \left\{\frac{\text{joules}}{\text{sec.}}\right\} \times \left\{\text{secs.}\right\}$$

or 11.0 joules.
Prof. Friedman summarizes the above reasoning by the one formula:

$$\left\{\frac{\text{Force}}{\text{el.ch.}}\right\} \left\{\text{dist}\right\} \left\{\frac{\text{el.ch.}}{\text{sec.}}\right\} \left\{\text{time}\right\} =$$

Total energy transferred by the charges to the thick copper plate.
Giving *units* this would appear as follows:

$$\left\{\frac{\text{newtons}}{\text{el.ch.}}\right\} \times \left\{\frac{\text{m}}{1}\right\} \times \left\{\frac{\text{el.ch.}}{\text{sec.}}\right\} \times \left\{\frac{\text{sec.}}{1}\right\} =$$

newton–m = joules

5. By a demonstration of heat energy being generated in a piece of lead when it is struck with a hammer, one is reminded that kinetic energy completely turns into heat during a perfectly inelastic collision. Therefore, the kinetic energy of the electrons is going to be measured by noting the temperature rise of the copper plate when it is struck by the electrons. A thermocouple is used for this and it is observed that a 24-division deflection of the thermocouple meter corresponds to the predicted energy of 11 joules.

6. In order to check on the fact that such a deflection does indeed correspond to a gain in energy of 11 joules, the temperature rise of an identical copper plate is measured when 11 joules of mechanical energy from a falling weight is transferred to it by means of friction.

The data is as follows:
Mass of falling weight = 1.5 kg
Distance it falls = 1.5 m.
Therefore loss in mechanical energy is mgh
$= 1.5 \times 9.8 \times 1.5$
$= 22$ joules

Half of this is transferred to each of the two identical thick copper plates.

The thermocouple meter deflection was 23.5 divisions which checks that 11 joules went into one thick copper plate.

7. It is emphasized that just because the prediction worked with one set of values does not prove the general validity of the formula. (A check with a different set of values was actually done in the complete film.) The formula, by numerous experimental checks, has been found to be true for all cases.

8. Prof. Friedman points out that the prediction of the amount of energy transferred to the electron was done with no mention of the speed of the electron. This must mean that the force on the electron is independent of the speed when the charges on the plates are standing still. Prof. Friedman warns us that the force is not independent of the speed when the charges exerting force on the electron are moving.

9. He explains that this experiment also shows there is only one elementary charge in nature. He refers to the two kinds we dealt with in this experiment as the 'Millikan elementary charge' and the 'Faraday elementary charge'.

ADDITIONAL DISCUSSION

1. Prof. Friedman also stated that when the charges are accelerated over the same distance by the same force, they end up by moving about 1.5 times faster. When the force is doubled, the kinetic energy for elementary charge is doubled and hence, the speed is increased by a factor of $\sqrt{2}$ and $\sqrt{2}$ is approximately equal to 1.5.
2. To be sure that all of the 22 joules given up by the falling mass went into heating up the thick copper plates, the following precautions were taken when designing the apparatus:
a) the bearings supporting the axle were almost frictionless
b) the axle was insulated from the copper disc so that no heat would flow into it, and
c) the final kinetic energy of the falling mass was negligible compared to the total loss of its potential energy. This was achieved by adjusting the force of the spring which pressed the copper plates together.

Program 19
Electric Lines of Force and Electron Mass Determination

INTRODUCTION

This program is designed to provide a general survey of the types of force field which can be used to affect the motion of charged particles. It reviews certain aspects of the electric fields which have been read in the earlier chapters of the recommended text, and also the work on electromagnetism in the Grade 11 course. Both studies are a necessary preparation for the work on electromagnetic waves. The broadcast includes the PSSC films *Electric Lines of Force* featuring Dr. Alexander Joseph of Bronx Community College, New York, and *Electrons in a Uniform Magnetic Field* which features Prof. Dorothy Montgomery of Hollins College, Virginia. The second of these films shows an alternative method of determining the mass of the electron to the one described at the beginning of Chapter 28 of the PSSC text.

POINTS TO WATCH IN THE PROGRAM

1. The meaning of an electric force field is established.
2. Dr. Joseph uses a 7500-volt transformer of the type used in neon signs to produce his electric fields. As a safety factor, he connects a 20-megohm resistor in the circuit between each terminal of the transformer and the electrode which dips into the mineral oil.
3. Lines of force always leave the surface of the conductor at right angles. This can be seen clearly in each of the four different field patterns which Dr. Joseph demonstrates.
4. Certain 'properties of lines of force' are listed and one example of the usefulness of these properties is given.
5. The operation of an electron gun from a cathode ray tube is explained as a practical example of the application of electric fields. In particular, the electrostatic focussing of an electron beam should be noted.
6. The type of force field so far discussed is the type in which a fixed distribution of charge acts on a moving charge. With this type, the force on the moving charge is independent of its speed as was established in last week's program.
7. A review of the magnetic field around a straight conductor carrying a steady current is presented. It should be noted that this steady magnetic field results from a steadily moving electric field. Any charge moving perpendicular to this magnetic field experiences a thrust which is perpendicular both to the magnetic field and to its direction of motion. The strength of this thrust or force is *not* independent of the speed of the moving charge.
8. It should be noted that in the Leybold tube the electrons are acted on, in the first instance, by an electric field to give them kinetic energy, and then by a magnetic field which changes their direction but does not change their kinetic energy since the force exerted by the magnetic field is always perpendicular to their direction of motion.

9. The mass of the electron is determined as follows:

a) Since the P.D. in the electron gun was 100 volts and

$$1 \text{ volt} = 1.6 \times 10^{-19} \quad \frac{\text{joules}}{\text{el.ch.}}$$

and the Energy of a charge (q) accelerated through a P.D. of V volts is given by $E = qV$

$\therefore$ kinetic energy of an electron $= \frac{1}{2}mv^2 = qV$

$$\therefore \frac{1}{2}mv^2 = (1) \times 100 \times 1.6 \times 10^{-19} \quad (\text{el.ch.}) \left(\frac{\text{joules}}{\text{el.ch.}}\right)$$

$$\therefore \frac{1}{2}mv^2 = 1.6 \times 10^{-17} \text{ joules} \qquad (1)$$

b) The centripetal force on an electron in a magnetic field is given by $\frac{mv^2}{r}$ from dynamics and by Bqv from a knowledge of magnetic fields (see Sec. 30-8 in text).

$$\therefore \quad \frac{mv^2}{r} = Bqv$$

or $\quad mv = Bqr$

From a calibration curve for the Helmholtz coils, Dr. Montgomery finds the magnetic field strength for any given current in the coils.

She finds $B = .97 \times 10^{-22} \dfrac{\text{newtons}}{(\text{el.ch./sec.})(\text{meter})}$

$$\therefore \quad mv = .97 \times 10^{-22} \times 1 \times r$$

By means of a photographic 'trick' she finds

$r = .055$ m

$$\therefore \quad mv = .97 \times 10^{-22} \times 1 \times .055 \; \frac{\text{newtons}}{(\text{el.ch./sec.})(\text{meter})} \times (\text{el.ch.}) \times (\text{meter})$$

$$\therefore \quad mv = 5.34 \times 10^{-34} \text{ (newtons-sec.)} \qquad (2)$$

Solving equations (1) and (2) for m and v, we get

$m = .89 \times 10^{-30}$ Kg

$v = 6 \times 10^{6}$ m/sec.

10. The dependence of r on B and V is shown. If we solve equations (1) and (2) to get a value for r, we get

$$r = \sqrt{\frac{2m}{q} \times \frac{V}{B^2}}$$

and from this it can be seen that increased V increases r and increased B decreases r.

11. The magnetic focussing of an electron beam as used in a television tube or in an electron microscope is explained.

12. The force exerted by a moving magnetic field on a stationary charge is demonstrated. It is pointed out that this leads to the idea of electromagnetic waves.

Program 20
Electromagnetic Waves

INTRODUCTION

The aim of this program is to establish experimental evidence for the common properties of electromagnetic radiation over a wide range of wavelengths and thus establish the unity of the electromagnetic spectrum. This program, in conjunction with the reading of Section 31-9 of the PSSC text, will deal with the content of Section 4, Part IV of the course outline. The PSSC film shown in the program is entitled *Electromagnetic Waves* and it features Dr. George Wolga of M.I.T.

POINTS TO WATCH IN THE PROGRAM

1. The program opens with examples of electromagnetic waves from the radio wave part of the spectrum. It shows radio waves being used in the 'broadcast band', the 'short wave band', and the 'microwave region' (as used with radar).
2. The range of wavelengths in the electromagnetic spectrum is pointed out from a chart.
3. A list of the properties common to radiation from any region in the spectrum is given. These are:
   a) the energy travels from sender to receiver as a wave and therefore exhibits common wave properties
   b) the waves arise from accelerated charges
   c) all the waves travel with the speed of light, and
   d) the waves can be polarized and therefore are transverse waves.
4. Light being emitted from the electrons in a synchrotron is shown as proof that electromagnetic waves in the visible region of the spectrum arise from accelerated charges.
5. A double slit interference pattern, using a carbon arc source, is shown as evidence of the wave nature of visible light.
6. The polarization of light is explained and demonstrated as evidence that the waves are transverse.
7. The fact that X-rays arise from accelerated charges is explained.
8. An interference experiment with X-rays is performed. The interference takes place between waves being reflected from the planes of atoms in a crystal of lithium fluoride. A model of this type of interference phenomenon is demonstrated in the program by using a ripple tank before the actual X-ray experiment is performed. This establishes the wave nature of X-rays.
9. An experiment analogous to the double slit interference experiment previously performed with light is now shown with microwaves having a frequency of 9×10^9 cycles per second which corresponds to a wavelength of 3.3 centimetres. The microwaves are produced by a klystron tube and are led by means of waveguides to two horns which radiate the waves into space. The waves from the two horns start out in phase.

10. The fact that the waves are polarized is then demonstrated.
11. A metal reflecting screen is set up behind the receiving antenna and standing waves are produced. The distance between two nodes (i.e. $\frac{\lambda}{2}$) is measured and the wavelength is calculated. This turns out, as previously stated, to be 3.3 cm.
12. One is reminded that the speed of these microwaves can be easily measured by the 'radar technique', that is, by sending out a pulse of waves and measuring the time for the echo to return from an object a known distance away.
13. The final experiment in the program is performed with radio waves having a frequency of approximately 150 million cycles/sec. or a wavelength of about 2 metres. The fact that these longer wavelength waves also arise from accelerated charges and that they are polarized, is stressed.
14. The reasons for the belief in the unity of the electromagnetic spectrum are summarized.

(NOTE: The half-hour schedule of the program did not allow time for all the PSSC film to be shown and since the interference effects obtained with the radio waves were identical to those obtained with the microwaves, they were omitted.)

Program 21
The Rutherford Atom

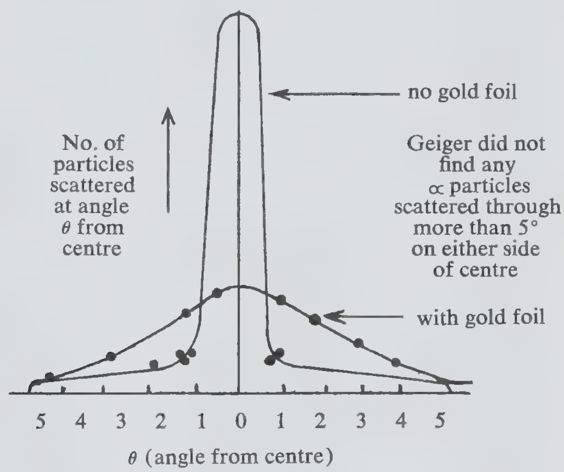
INTRODUCTION

This program introduces Chapter 32 of the PSSC textbook. The broadcast includes the PSSC film, *The Rutherford Atom* featuring Prof. Robert Hulsizer of the University of Illinois. By means of qualitative experiments and demonstrations with models, the ideas leading to Rutherford's nuclear model of an atom are strikingly presented. Following this, the film illustrates how Rutherford's prediction of a Coulomb Force Law of repulsion for alpha particles colliding with the nucleus was verified by Geiger and Marsden.

MAJOR POINTS TO LOOK FOR IN THE PROGRAM

1. A reminder of the nature of alpha particles.
2. A comparison of the length of particle tracks in air without, and then with, a piece of gold foil in front of the radioactive source (polonium). The two distances, or the longest tracks, are about 4 and 3 scale divisions respectively.
3. A comparison is made of the distribution of alpha particles within a narrow beam before and after a piece of gold foil is placed in the path of the beam. The following graphs (Figure 1) show the results of Geiger's original experiment.

Figure 1



4. A qualitative experiment showing the distribution of alpha particles in a wider beam (70°) is then illustrated. After finding and marking the edges of the beam, the detector is moved 25° out of the beam and the discovery of wide-angle scattering is made.
5. A model is introduced which shows hot steel ball-bearings (representing alpha particles) being rolled down a ramp on to a sheet of waxed paper and then passed through a region which represents the gold foil. The hot balls leave tracks in the waxed paper so that it can be detected whether or not any collisions took place while the particles were passing through the gold foil. It was observed that only six collisions took place out of approx-

imately 200 tracks. On examining the model of the gold foil, it was found that there were hard steel pins at the places where the large deflections took place and that the rest of the space consisted of soft felt only. This leads to the idea of an atom consisting mainly of empty space which has the very light negatively-charged particles in it and with all the rest of the mass of the atom being very concentrated in a minute space at the centre. Furthermore, this massive core carries a large positive charge and this explains the wide deflections of the positively charged alpha particles.

6. The remainder of the film shows how Rutherford checked this view of the atom. He did this by finding out from a detailed study of the deflection angles what type of collision took place between the alpha particles and the nucleus. By 'type of collision' is meant the kind of force law which exists between the colliding bodies.

Prof. Hulsizer demonstrates three possible types of collisions:

a) Magnetic collisions in which the force of repulsion obeys an inverse cube law
b) Contact or hard sphere collisions in which the force of repulsion arises very abruptly
c) Electrostatic or Coulomb collisions in which the force of repulsion obeys an inverse square law.

For the same incident path each of these produces a different deflection angle after collision.

7. Rutherford suspected a Coulomb type interaction, and on this basis he calculated the angles through which the alpha particles would be deflected as a function of how directly they were aimed at the centre of the atom. All the different paths or trajectories are found to be hyperbolae. Prof. Hulsizer shows some of these in a model of an atom.

8. Graphs of the number of alpha particles expected at each deflection angle for each kind of collision are shown. These are reproduced herewith (Figure 2), and we can see how Rutherford's prediction was verified.

9. Prof. Hulsizer summaries the views on the structure of the atom based on the above results. He states that Rutherford was also able to estimate the size of the nucleus and he shows, by means of a model, the relative dimensions of the whole atom and the nucleus in order to emphasize that most of the atom consists of empty space.

10. The program concludes with a brief discussion on the limitations of the Rutherford model of the atom and a suggestion that a new look at the nature of light will provide a clue to solve the difficulties.

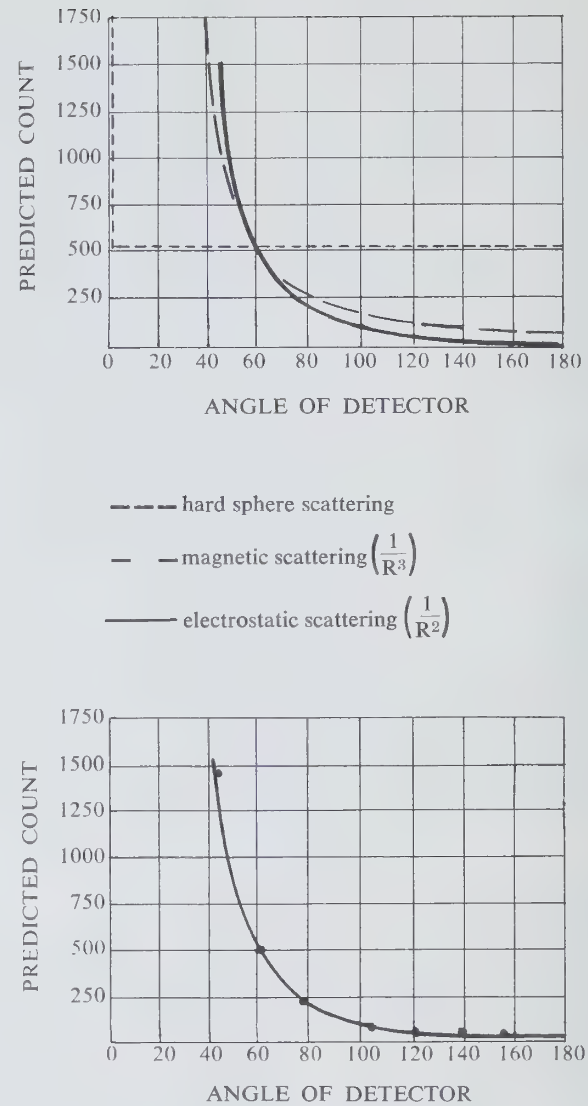


Figure 2

The dots represent Geiger and Marsden's experimental results. They are compared with the curve characteristic of a $\left(\frac{1}{R^2}\right)$ force as predicted by Rutherford.

ADDITIONAL DISCUSSION

It should be pointed out to the students that the scattering curves and experimental verification in this program are not the same as those discussed in the PSSC textbook. In the broadcast, the description is in terms of the number of particles scattered into a small angular range located at an average angle θ, whereas the PSSC textbook considers the total number of particles scattered through angles greater than some angle θ.

Program 22
Random Events

Although this program has considerable general interest, its main value to the Grade 13 student at this time lies in its relationship to Section 33-2 of the text and to the phenomena in the next program. The broadcast shows almost all of the PSSC film *Random Events* with Prof. Patterson Hume and Prof. Donald Ivey of the University of Toronto.

MAJOR POINTS OF THE PROGRAM

1. The purpose of the film is stated in a sentence: "Random events are events which occur with no order, that is, unpredictably, and yet the overall effect of a very large number of such events can be very predictable indeed."
2. An example of random events occurring naturally is shown with a geiger counter detecting the radioactive disintegration of polonium. It is not possible to predict when any single disintegration will occur. However a graph such as that on p. 131 of the text is designed to predict the activity of polonium at any time in the future. Prof. Hume explains the meaning of the 'half-life' of a radioactive substance and states that the graph of radioactivity is the same for all radioactive substances. He asks, "How can this predictable behaviour emerge from the unpredictable behaviour shown by the geiger counter?"
3. To show how this can be answered, several mechanical illustrations are used. The first of these is a type of pinball machine in which marbles starting at the top-centre of a slope roll down through a maze of pegs into parallel equally spaced slots at the bottom. When using 100 marbles at a time, the frequency distribution of the marbles in the slots is different every time. With 1,000 marbles at a time, the fluctuations in the frequency distributions are much smaller. By averaging three 1,000-marble frequency distributions, Dr. Ivey gets a distribution which is reasonably close to the true frequency distribution. Using this, it is possible to make statistical predictions about the behaviour of marbles in the pinball machine *if you use a large number of marbles.* A single marble still behaves unpredictably.
4. The second illustration consists of a large square in a wall made up of 16 square cards which are free to rotate. Each card is black on one side and white on the other. Since white reflects light and black does not, the number of white cards facing out is quickly counted by means of a light meter facing the wall. When all white cards face out, the meter reads 16; with all black, zero, and with half white and half black it reads 8. When the cards are all spun freely and then stopped, how many white cards will face out? There are 17 different possible answers but we expect to get a reading of 8 on the meter most of the time.

Dr. Hume tries the experiment a few times and gets considerable fluctuations from this. He then shows that for this apparatus it is possible to *calculate* the probability of getting each of the 17 different possible results. The calculation is based on the assumption that black or white facing out is equally probable for each card. He emphasizes that any such calculation must be checked experimentally. He then moves to another large square of the same size but which is made up of 256 cards. This time a reading of 8 on the meter (representing half white and half black) is so much more probable that he can say almost with certainty that he will get 8 any time he tries it and he does. This again shows that the effect of a very large number of random events is very predictable.

5. Dr. Ivey then returns to the example of radioactivity. To talk about the activity of a radioactive material means that there are a certain definite predictable number of disintegrations in a given length of time. He shows a geiger counter held at a distance from a sample of polonium and there are few counts which are very random. When the counter is moved close to the sample, the count rate becomes much greater. At this fast rate the counts in the units column are very random; in the tens column they are still random; but in the hundreds column the counts become quite regular. If the thousands column had been observed they would have been much more regular. This again emphasizes that only the effect of a very large number of random events is predictable.
6. Dr. Hume now explains why the radioactivity decreases in the particular way shown by the graph on p. 131 of the text for *all* radioactive substances. Radioactive behaviour is simulated by a game of dice. Starting with 60 dice in a box, the dice are thrown; all those which turn up a five represent atoms which have just disintegrated and therefore the number of fives is a measure of the 'activity' of the sample. All the fives are removed after each throw and piled in a column to indicate the activity at that particular time. This is repeated a large number of times. The law of chance for this game is that the chance of a five turning up is exactly the same each time the dice are thrown. It does not change with time. This agrees with the law of radioactivity in that the chance of an atom disintegrating is always the same. Again we see an orderly behaviour only if the time for a very large number of counts is used as a measure of activity.
7. Orderly behaviour is observed in all the measurements that we make. The measurement of light intensity is used as an example. The question is raised whether orderly behaviour always arises from random events. The question can be answered only from experiments. Order sometimes does have randomness (which is not apparent) at its roots. How can we tell whether randomness does underlie an observed orderly behaviour or not? The answer is, reduce the number of events observed in a given time. This is demonstrated with light by cutting down the light intensity and then using a very sensitive detector connected to a cathode ray oscilloscope. The arrival of individual photons is seen, which indicates that the orderly behaviour of light does have randomness at its roots.

POINTS FOR FURTHER AMPLIFICATION AND DISCUSSION

1. The frequency distribution curve obtained with the pinball machine approximates what is called a Gaussian frequency distribution. It is not the same type of distribution curve as is obtained with the card machine which is a binomial distribution.
2. Students of algebra will probably recognize that the relative probabilities for each of the 17 different possible results with the 16 black or white cards are given by the coefficients of the binomial expansion of $(a + b)^{16}$. Since these coefficients for the first nine terms are 1, 16, 120, 560, 1820, 4368, 8008, 11,440, and 12,870, it can be seen why Dr. Hume said that the frequency distribution was plotted to a greatly reduced scale. It can also be seen why the probability of getting a reading of 8 on the meter with the 256 cards is so great because the coefficient of the middle term in the expansion of $(a + b)^{256}$ is such a huge number. When the 257 coefficients are reduced to the same scale as the 17 in the previous example, the much narrower and higher probability curve is obtained.
3. A student wishing to find out more about the theory of probability could be referred to the book *Lady Luck: The Theory of Probability* by Warren Weaver. This is one of the inexpensive Science Study Series paperbacks.
4. Some other examples of orderly behaviour which has randomness at its roots are the measurement of gas pressure and the measurement of electric current. It would be worthwhile for the student to think of *evidence* for the randomness which underlies these measurements.

Program 23
Photons and Interference of Photons

INTRODUCTION

In this program two PSSC films are shown, namely, *Photons* and *Interference of Photons*. Both films feature Prof. John G. King of M.I.T. In the first film, an experiment is performed to demonstrate the particle nature of light and this relates to the study of Section 33-1 of the PSSC textbook. The second film demonstrates both the wave and particle nature of light in one experiment in which an interference pattern is examined with a photomultiplier. The second film relates to the study of Section 33-3 of the PSSC textbook.

MAJOR POINTS OF THE PROGRAM

PART I

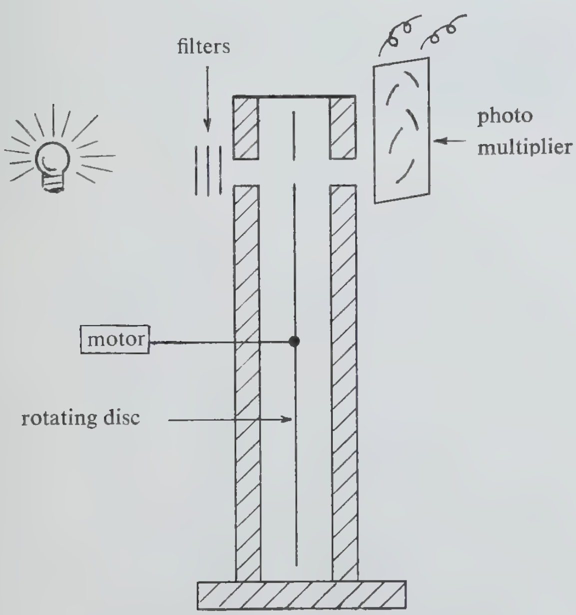
1. The viewer is reminded of some features of the behaviour of light which could not be explained by the classical electromagnetic wave theory of light.
2. Prof. King states that very weak light must be used in order to see the effect of individual light particles.
3. To study the light, a photoelectric cell is used. When light strikes the cathode in a photoelectric cell, electrons are given off and these are collected by a positive anode. The current through the cell is proportional to the amount of light striking the cathode. For the very weak light used in this experiment, the current is so small that an amplifier is needed to measure it. The amplifier which Prof. King uses is a photomultiplier tube. This is a photoelectric cell with an amplifier built inside the same bulb. Prof. King explains the operation of such a tube, and establishes that it amplifies the initial current from the cathode by a factor of about a million.
4. The output of the photomultiplier is fed into a cathode ray oscilloscope and its response, first to strong light and then to very dim light, is demonstrated. He then explains that although pulses are seen in the second case, it does not necessarily prove that light comes in particles. He explains that even when no light falls on the photomultiplier, there are still some pulses. (These background pulses are a result of thermal agitation of the electrons.) This thermal background or 'noise' can be almost eliminated by cooling the tube. Prof. King does this with a mixture of dry ice and alcohol.
5. Prof. King then explains his outline for the main experiment. On the basis of the wave theory, light energy falls on a surface in a continuous stream, whereas in the particle theory, light energy is given to a surface in discrete bundles in a random manner. Consequently in the first case, one would have to wait a definite length of time after the light was turned on before electrons in a metal surface would gain enough energy to cause photoelectric emission. In the second case, an electron would receive all the necessary energy in a moment and be emitted, and this could occur immediately after the light was turned on, or after any other random length of time.

Prof. King makes a comparison between this process and the delivery of milk. Suppose a person requires a quart of milk once a minute. The milk could be delivered in one of the following ways:

a) by a pipe in which the milk flows at the rate of one quart every ten seconds. At the beginning of every minute a gate opens and the milk flows; after a 10-second wait a quart bucket would be filled and then the gate closes. (Consider the milk as the light energy and the bucket as the electron which must receive a certain amount of energy before it can be emitted), or

b) by a conveyor belt on which quart cartons of milk are placed at random intervals and when a gate at the end of the belt opens, the belt starts to move. The gate opens for ten seconds once every minute, and on the average, the person receives one quart a minute. In this case, however, he might receive his quart immediately after the gate is opened or he might have to wait 5 or 10 seconds, or in one 10-second period he might not get any milk and the next time he would get 2 quarts. All this could happen because of the random distribution of the packages on the conveyor belt. This, of course, is comparable to electrons being emitted in a photoelectric cell at random time intervals after the light is turned on, rather than always having to wait a full 10 seconds. It is this idea which Prof. King uses to find out whether light energy comes in packages (photons).

6. The 'gate' corresponds to a shutter, consisting of a rotating disc between two black walls. When a hole in the disc lines up with the hole in the walls, the light gets through. This occurs for a brief instant once every revolution.



7. Filters are inserted between the source of light and the photomultiplier to reduce the light intensity by a factor 10^6. The output of the photomultiplier is then seen to be 3×10^{-10} amperes. Therefore, the input of the photomultiplier is 3×10^{-16} amps. Since 1 amp $= 6.25 \times 10^{18}$ el.ch/secs., this corresponds to $3 \times 10^{-16} \times 6.25 \times 10^{18}$ which is roughly 2,000 electrons per second or, on the average, 1 electron every $\frac{1}{2000}$ sec. This corresponds to the idea of 1 quart of milk in every 10 second interval (on the average).

8. The shutter disc is spun at 60 revs/sec. and Prof. King estimates that the shutter is open for $\frac{1}{5000}$ sec. every $\frac{1}{60}$ of a second. The lamp is shone through without filters and the pulse from the photomultiplier is fed into the cathode ray oscilloscope, and the $\frac{1}{5000}$ sec. time interval is marked on the screen.

9. The three filters are then inserted so that one is brought back to the case of 1 electron being emitted every $\frac{1}{2000}$ sec. If light comes in a continuous stream one should have to wait $\frac{1}{2000}$ sec. before an electron is emitted. Since the shutter is open for only $\frac{1}{5000}$ sec. after the light starts to show through, one should not get any pulses in this time interval. However, we do get pulses, some even within 6 microseconds after the shutter began to open. This means that light does not deliver its energy in a continuous stream but in particles. These particles are called photons. They are not like the simple particles referred to in Chapter 14 of the PSSC textbook, because they are intimately connected with waves as will be witnessed in the next film.

ADDITIONAL DISCUSSION

1. The experiment shown in the film cannot, on its own, conclusively demonstrate that light comes in packages. Additional experiments are necessary before one is justified in coming to a definite conclusion. These experiments involve a study of the mechanism of the absorption of light at the photocathode which leads to the emission of electrons and also a consideration of the efficiency of the cathode in the photomultiplier (i.e. what percentage of photons actually produces a photoelectron and what percentage is just 'lost' in the surface). These and other experiments have been performed and all conclusively support the idea of photons.

2. Students may rightly question whether the pulse seen at 6 microseconds after the shutter began to open is the result of a thermal electron or a photoelectron. However, since only one event is shown, it is statistically insignificant. This problem can only be solved by comparing the number of pulses seen at 6 microseconds which occur when the light is on, with the number of pulses seen with-

out a light. This experiment, however, would have taken too much film time to perform.

3. The students will get a better idea why a smooth pulse is seen with strong light but a very erratic pulse is seen with weak light if they view the PSSC film, *Random Events*. This was the main purpose of the previous broadcast.

(NOTE: After a short pause in the broadcast, the film, *Interference of Photons* is shown without any introduction because it carries on quite smoothly from the last remarks in the *Photons* film.)

MAJOR POINTS OF THE PROGRAM

PART II

1. Prof. King describes the apparatus with which he is going to show both the wave and particle nature of light in one experiment.

A diagram of the apparatus is illustrated below.

2. Without dimming the light source, Prof. King moves the double slit back and forth and shows that he alternately gets a maximum and minimum. In other words, there is an interference pattern. He then leaves the double slit in such a position that the central maximum is on the photomultiplier slit.

3. The light source is dimmed so that the current coming out of the photomultiplier is 10^{-9} amperes.

4. The output of the photomultiplier is then put on a cathode ray oscilloscope and also fed through an amplifier into a loudspeaker. The double slit is then moved back and forth as before, and again maximum and minimum are observed. When a maximum is on the photomultiplier slit, pulses are seen on the C.R.O. screen. Prof. King emphasizes that they are caused by photons.

5. He then explains that there is rarely more than one photon in the box at any one time. He explains this in the following manner:

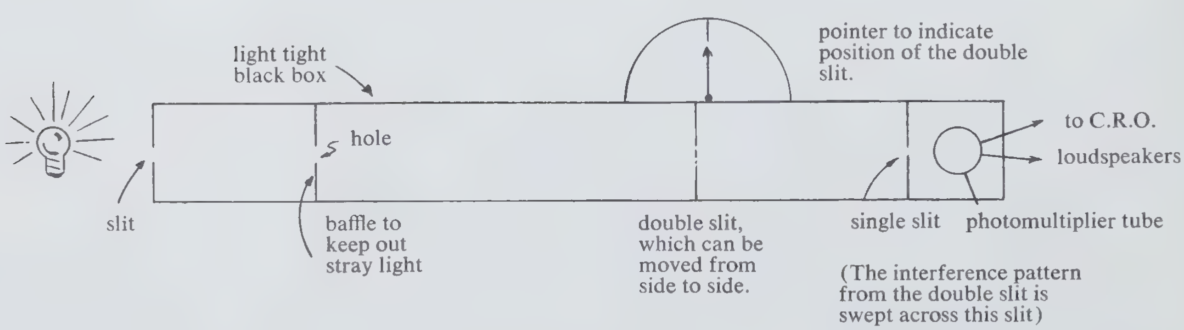
a) Output current of photomultiplier is 10^{-9} amps. But amplification factor of the photomultiplier is 10^6. Input current of photomultiplier is 10^{-15} amps, or $6.25 \times 10^{18} \times 10^{-15}$ electrons/sec. which is approximately 10,000 electrons/sec.

b) The efficiency of the photocathode is approximately 10^{-3}. (This is a very conservative estimate.) This means that, on the average, 1,000 photons must strike the photocathode in order to emit one electron, and that $10^3 \times 10^4$ photons must enter the photomultiplier slit each second in order to produce a current of 10,000 electron/sec.

c) If 10^7 photons are passing through the box per second, then 1 photon enters the box, on the average, every 10^{-7} seconds.

d) Since photons *are* light, they travel at the speed of light, i.e. 3×10^8 m/secs. If photons enter the box one every 10^{-7} sec., this means that when one photon is entering the box, the one before it has already been travelling in the box for 10^{-7} seconds. In short, it has travelled $3 \times 10^8 \times 10^{-7} = 30$ m. or 100 ft. The box, however, is only 8 ft. long, therefore, in the main, there is only one photon in the box at a time, that is, one photon has passed through the double slit and hit the photomultiplier long before another photon enters the box. The remarkable fact is that the interference pattern is characteristic of individual photons rather than the interaction between two or more photons.

6. Prof. King points out that light, as distinct from any previously discussed models, behaves like particles and waves at the same time. One interprets this interference pattern (wave behaviour) of photons by stating that the probability of the arrival of photons at one place is given by the intensity of the pattern at that place. Where there is a maximum of intensity one is most likely to find photons. Where there is a minimum, one will find none.



Program 24
Matter Waves

INTRODUCTION

This program presents the PSSC film, *Matter Waves* featuring Prof. Alan Holden and Dr. Lester Germer of Bell Telephone Laboratories, New Jersey. It shows experimental evidence for the wave behaviour of particles of matter by showing that electrons produce interference patterns. (The broadcast refers directly to Section 33-8 of the PSSC textbook.)

MAJOR POINTS OF THE PROGRAM

1. Louis de Broglie in 1923 suggested that waves are also associated with ordinary particles of matter. In 1927 Davisson and Germer in New York City and G. P. Thomson in Cambridge, England, performed diffraction experiments showing that the De Broglie idea was right.
2. A shadow of an object may be cast by spraying particles at it, such as paint from a spray gun. This is the idea used in an electron microscope. Beams of electrons cast enlarged shadows of small objects on a photographic plate. An electron microscope photograph of smoke particles shows an interference pattern at the edges of the shadows of the particles. This is compared with the light and dark bands seen at the edges of the shadow of a razor blade illuminated by a small source of light. Hence a study of diffraction patterns is going to be used to check up on the idea that electrons behave like waves.
3. We are reminded of the behaviour of light where it strikes a diffraction grating. The spacing between the lines must be comparable to the wavelength of the waves we wish to diffract.
4. De Broglie's suggestion that the relationship $p = \frac{h}{\lambda}$ (where p is the momentum of a photon) should also hold for matter waves, is used to get an idea of the wavelength of the matter waves, and hence give us some idea of the line spacing needed to show a diffraction pattern with electrons.

Using this idea, the calculation is as follows:

Mass of electron $\approx 10^{-30}$Kg

Speed of electron when accelerated through a P.D. of 100 volts $\approx 10^{7}$ m/sec.

$\therefore$ p of electron $\approx 10^{-23}$ newton-sec

$$\because\ p = \frac{h}{\lambda}$$

$$\lambda = \frac{h}{p} = \frac{6.62 \times 10^{-34}}{10^{-23}}\ \frac{\text{joules-sec}}{\text{newton-sec}}$$

$$\therefore \lambda \approx 10^{-10}\ \text{m}.$$

This is about the size of an atom.

5. A grating with this spacing is obtained by using the orderly arrangement of atoms in a crystal. However, in this case the lines are in two perpendicular directions. The effect of using two single line gratings, one placed on top of the other, and the two sets of lines perpendicular to each other, is then illustrated. White light is first used followed by blue light to show the effect of different wavelengths.
6. An apparatus which will be used to perform a comparable experiment with electrons is then described. A beam of electrons is reflected from the surface of a crystal onto a fluorescent screen which shows the diffraction pattern.
7. The scene changes to the Bell Telephone Laboratories in New Jersey where Dr. Germer performs an actual experiment with the apparatus described. He first uses 40 volts to accelerate the electrons and get a diffraction pattern typical of 'crossed gratings'. He then uses a higher voltage (47 volts). This means higher speed, therefore there is larger momentum, and shorter wavelength. This means that the pattern should shrink and it does so. Dr. Germer states that knowing the spacings of the atoms in the crystals and the angle of the beams in the diffracted electron pattern, he can calculate the wavelength of the electrons. This is exactly what he and Dr. Davisson performed in 1927 and he shows one of the first experiments taken from their original apparatus. He also states that they performed the first experiment in which electron diffraction was observed.
8. Dr. Holden then describes the experiment which G. P. Thomson performed in Cambridge at about the same time. The main difference in the two experiments is that Thomson, using higher voltages, shot the beam of electrons right through the crystal. Transmission through a grating gives exactly the same effect as reflection from it. However, in going through a layer of crystals, the beam meets many gratings at random angles and a circular diffraction pattern is obtained instead of dots. He compares photographs taken by X-rays with one taken by electrons to show the close similarity.
9. Dr. Holden illustrates that *any* particles show this wave behaviour and not just electrons. He shows diffraction patterns obtained with beams of helium atoms and with beams of neutrons.
10. The program concludes with the idea that the wave-like behaviour of material particles is so well established that this fact is used as a tool in other research, for example, to find out more about the arrangement of the atoms in other crystals.

ADDITIONAL DISCUSSION

1. Dr. Davisson and G. P. Thomson shared the Nobel Prize in Physics in 1937 for their work on these experiments.
2. G. P. Thomson was the son of Sir J. J. Thomson. It is interesting to note that prior to J. J. Thomson's experiments in 1898, streams of electrons were called cathode rays. Then J. J. Thomson received the Nobel Prize in 1907 for showing the corpuscular nature of electrons and his son received the same prize thirty years later for showing the *wave* nature of electrons.

Program 25
The Franck-Hertz Experiment

INTRODUCTION

This program presents the PSSC film, *The Franck-Hertz Experiment* featuring Prof. Byron L. Youtz of Reed College, Portland, Oregon. The aim of this program is to show that atoms can take on only certain definite amounts of energy which also means that they can exist only at discrete energy levels or states. In the broadcast, a slightly modified version of the original Franck-Hertz experiment is performed. It shows that when an accelerated electron makes an inelastic collision with a mercury atom, the smallest amount of energy it can give is 4.9 electron volts. The program relates directly to Sections 34-1 and 34-2 of the PSSC textbook.

MAJOR POINTS OF THE PROGRAM

1. A photograph of the bright line spectrum of mercury in both the visible and ultraviolet regions recalls the fact that mercury atoms emit light only at certain distinct frequencies and wavelengths. Attention is directed to the line representing a wavelength of 2537 Angstroms. Since light energy comes from atoms in photons whose energy is proportional to the frequency, all photons coming out of the atom to make up this spectral line will have the *same energy*. The energy of each photon is given by the formula $E = \frac{12397}{\lambda}$ where λ is in Angstroms and E is in electron-volts.

2. If atoms lose energy in certain discrete bundles of energy, it seems reasonable to suggest that they can only absorb energy and be raised from one energy state to a higher one in steps having the same discrete energy values. The question then is, "Can we cause a mercury atom to move from one energy state up to another energy state by a process which does not use photons?"

Can we, for example, make an electron collide with a mercury atom and give it just the right amount of energy to cause it to jump from one energy state to another?

3. This idea was tested in 1914 by James Franck and Gustav Hertz who were studying elastic and inelastic collisions between electrons and atoms, and the relationship of this to the emission of light.

4. A mechanical model consisting of a dry ice puck (representing a mercury atom) and a ping-pong ball (representing an electron) is used to illustrate the nature of elastic and inelastic collisions. The model, however, cannot establish the idea of absorption of energy only at discrete energy levels.

5. The construction of the special vacuum tube used in the actual experiment is illustrated.

The function of the parts is described by means of a schematic drawing.

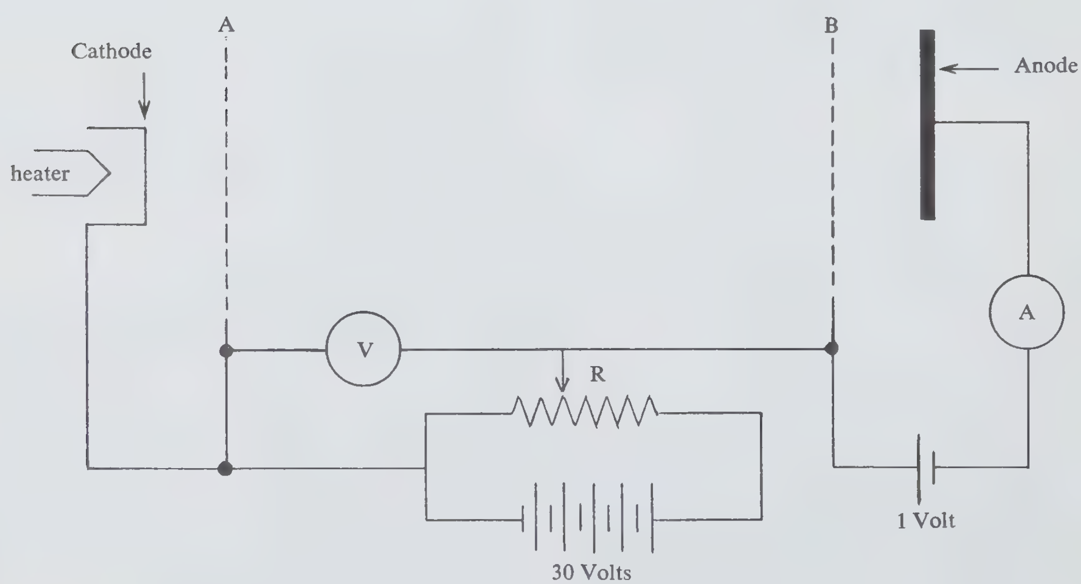
The control grid A limits the number of electrons passing into the region between A and B.

B is the accelerating grid.

V measures the voltage between A and B which is accelerating the electrons across the gap.

This voltage can be varied by means of the potentiometer R.

The anode is held at a potential which is 1 volt nega-



tive with respect to B. Therefore, electrons which pass through B must at least have an energy of 1 electron volt in order to reach the anode and be counted by the current meter A.

6. Prof. Youtz shows that with very little mercury vapour between A and B, the current rises smoothly as the voltage is increased up to 30 v.

7. Mercury atoms are introduced into the path of the electrons by placing the tube (which has a large drop of mercury in it) into an oven at about 160°C.

8. Prof. Youtz now predicts that if the voltage is raised as before, the current will rise until a voltage is reached at which the electrons gain just the right amount of energy to deliver the proper sized package to the mercury atoms near grid B. Then they will not have enough energy left to get up the potential kill between B and the anode, and so the current will drop.

9. He performs the experiment and the prediction seems to be correct. He then continues to increase the voltage and the current continues to rise and fall alternately.

10. Prof. Youtz then repeats the experiment and makes a record of current versus accelerating voltage on an X-Y recorder.

The graph he obtained is similar to the one shown below:

On the average, the distance between peaks is about 4.9 volts. Two possible interpretations of this are given. It is shown that, in either case, it may be concluded that the smallest package of energy which a mercury atom can accept is 4.9 electron-volts.

11. This is checked against the relationship $E = \frac{12397}{\lambda}$ for the energy of photons emitted by an atom. For the spectral line $\lambda = 2537$ Angstroms $E = \frac{12397}{2537} = 4.9$ e.v.

This is an exact agreement with the prediction.

12. Prof. Youtz briefly discusses possible new experiments which should be performed to check up on this new theory.

ADDITIONAL DISCUSSION

1. In the complete film, *The Franck-Hertz Experiment,* there is an epilogue by Prof. James Franck in which he describes an experiment where 4.9 e.v. electrons were used to bombard mercury atoms. The emission of these energy packages in the form of photons to produce the single spectral line of 2537 Angstroms was then observed. This provided an excellent check on the theory.

2. In 1925 Professors Franck and Hertz shared the Nobel Prize in Physics for their research in connection with the energy states of atoms.